Bulletin
of
The Geological Society of America

VOLUME 64 February 1953 NUMBER 2

CONTENTS

	Pages
Safeguarding our mineral-dependent economy. By T. S. Lovering	101–126
Examination of the physics of theories of orogenesis. By Adrian E. Scheidegger	127–150
Geology of Agua Fria quadrangle, Brewster County, Texas. By C. Gardley Moon	151–196
Bibliography and index of literature on uranium and thorium and radioactive occurrences in the United States. Part 1: Arizona, Nevada, and New Mexico. By Margaret Cooper	197–234
Beaverhead formation, a Laramide deposit in Beaverhead County, Montana. By Wayne Russell Lowell and Montis R. Klepper	235–244
Short Notes	
Evidence for variable vertical movement in central Utah. By Clyde T. Hardy	245–248
Seismic-refraction profile across the Gulf of Maine. By Samuel Katz, Richard S. Edwards, and Frank Press	249–252
Age of a Mid-Atlantic ridge basalt boulder. By Donald R. Carr and J. Laurence Kulp	253–254

Subscription $15.00 per year.

Publication Office: Mt. Royal & Guilford Aves., Baltimore 2, Md.

Communications for publications should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117 Street, New York, N. Y.

NOTICE—Four weeks notice of change of address is necessary. In accordance with the rules established by the Council, claims for non-receipt of the preceding number of the Bulletin must be sent the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter at the Post-Office at Baltimore, Md., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103 Act of October 3, 1917, authorized on July 8, 1918.

PAPERS IN PRESS FOR FORTHCOMING ISSUES

REVIEW ISSUE:

REVIEWS OF GEOLOGIC LITERATURE: AN INNOVATION
METAMORPHISM OF BASALTIC ROCKS: A REVIEW. By Arie Poldervaart
FOSSILS IN METAMORPHIC ROCKS: A REVIEW. By Walter H. Bucher
NONRADIOGENIC ISOTOPES IN GEOLOGY: A REVIEW. By Earl Ingerson

SAN ANDREAS, GARLOCK, AND BIG PINE FAULTS, CALIFORNIA. By Mason L. Hill and T. W. Dibblee, Jr.

SILICEOUS SEDIMENTS OF OUACHITA FACIES IN OKLAHOMA. By August Goldstein, Jr., and Thomas A. Hendricks

GEOLOGY OF THE CHLORIDE QUADRANGLE, ARIZONA. By Blakemore E. Thomas

CENOZOIC FILL AND EVAPORITE SOLUTION IN THE DELAWARE BASIN, TEXAS AND NEW MEXICO. By V. C. Maley and Roy M. Huffington

MUDFLOW OF 1941 AT WRIGHTWOOD, SOUTHERN CALIFORNIA. By Robert P. Sharp and Laurence H. Nobles

PLEISTOCENE GEOLOGY OF PART OF CENTRAL SOUTH DAKOTA. By Dwight R. Crandell

RELATION OF GRAVITY ANOMALIES TO THE GEOLOGY OF CENTRAL VERMONT AND NEW HAMPSHIRE. By Robert J. Bean

Note: Reprints of ***Bibliography and index of uranium and thorium, and radioactive occurrences in the United States,*** by Margaret Cooper, printed in this issue (p. 197–234) are available. Price 25 cents. Remittance should accompany order.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 64, PP. 101-126, 8 FIGS. FEBRUARY 1953

SAFEGUARDING OUR MINERAL-DEPENDENT ECONOMY

(Address of the Retiring President of The Geological Society of America)

BY T. S. LOVERING

ABSTRACT

The American economy is built around the manufacturing and construction industries, which in turn are dependent on mineral supplies.

Our economy has flourished under economic philosophy rooted in the free enterprise system, but both are changing radically. Our basic belief has been that competition, with an absolute minimum of government interference, is the best possible way to achieve lowest cost, highest quality, and the largest quantity of any particular goods for the consumer. This requires competition among laborers for jobs and competition among manufacturers for markets. Competition in labor means a permanent reservoir of temporarily unemployed and less security for the worker. To maintain competition for markets requires that the consumption of goods be less than the production of goods, and requires also that the purchasing capacity of the consumer be less than the potential productive output of the economy. Overproduction is a prime cause of business failures, but the more business failures per year the lower the cost to the consumer with a fixed income. To work successfully, the free enterprise system obviously requires a delicate adjustment of conflicting interests, an optimum percentage of business failure, an optimum percentage of unemployed, and an optimum relation of production to demand and purchasing power.

Government-controlled private enterprise became necessary during World War II in the United States, and prices, credit, purchases, and employment were all managed by government agencies, although the man above draft age was relatively free to choose his occupation or business. Government-controlled state enterprise ranges from relatively democratic socialism to the Communist police state. In contrast with free enterprise the latter fixes the quality, quantity, wages, profits, prices, kind of merchandise, and its distribution. In theory this type of economy permits planning for national objectives and utilization of the nation's resources to the best advantage for both short- and long-range needs. Against this is the difficulty of providing incentives to produce more, better, cheaper; the problem of getting efficiency in government controlled industry; the lack of freedom of labor to bargain with its employer; and the determination of kind, quality, and quantity of goods by bureaucrats rather than by consumer demand.

Our current industrial economies are all dynamic, and their industries show characteristic sigmoid growth curves when output is plotted against time. When industrial maturity is reached the percentage increase diminishes until it is no greater than the percentage increase of the population. This stage corresponds to a flattening of the sigmoid curve, and, as our industrial economies represent a summation of the industries of the country, it is evident that the percentage increase in production of the manufacturing segment of the economy as a whole must eventually drop. In an agriculturally self-sufficient nation the growth of production will closely parallel the growth rate of the population, if surpluses or deficiencies are avoided.

The products of industry are sold to four types of markets: domestic consumer market, the inter-industry or plant-expansion market, the government market, and the foreign market. The first two are of prime importance in the early stages of industrialization, but in time the consumer market tends to level off at a certain per-capita figure, determined in large part by the median wage paid to the industrial worker rather than by the satisfaction of his desire for goods. This reflects the multiplication of production by machinery and the fact that the labor force in general produces much more than it purchases, after the plant-expansion market has decreased in importance. This commonly leads to either unemployment or to the government subvention of industry through artificial markets supported by loans largely from the higher-income groups.

In the past the artificial market supported by our national government has fluctuated tremendously, but its varying importance is clearly shown by changes in the national debt which have a conspicuous correlation with wars and times of crisis. Each major war saw an increase in the national debt over that incurred in the preceding war by a factor of about 10. Artificial peace-time markets became an important factor in

our national life in the 1920s, with private and government loans, later repudiated, to build up the devastated areas of Europe. During the 1930s the government began to subsidize the national economy on a large scale, and after the depression it continued to do much to bolster our economy by increased military expenditures.

It has become apparent gradually that the distribution of income is a political decision, and during the past half century both labor and the farmer have voted consistently in such a way as to bring strong pressure to bear on the Congress to redistribute income to their benefit. The organization of labor has been of immeasurable benefit to many lower-income groups, and the parity price-support program for the farmer similarly has helped their income tremendously. The change in our political, social, and economic philosophy has now reached the place where the government is charged with the responsibility of maintaining full employment, and to do this it spends large sums to maintain artificial markets. Loss of these markets supported by gigantic public funds would now cause a chaotic dislocation in our economy, and I am forced to the conclusion that we should expect changes but *not* diminution in our artificial markets.

The situation that we have reached is vividly shown by a chart indicating steel output (Fig. 8). The amount of per-capita steel output required to maintain full employment has increased constantly as the efficiency of industrial processes has increased, but the market dependent on unsubsidized consumer demand leveled off between 700 and 800 pounds per capita years ago. There is a steadily growing spread between the curve representing per-capita consumer demand and the curve for per-capita steel consumption under full employment, which has tremendous economic, political, and social implications for the future. It emphasizes our major problem, the bald fact that our labor force can produce much more than its wages buy with the present distribution of income, and challenges our entire economic philosophy.

Drastic changes may be in the offing, but we will not return to an agricultural economy; the mineral industry on which our industrial plant is utterly dependent is seeing constant changes in its own economic position, with attendant social and political problems.

It is impossible to say when the mineral deposits supplying our industry will become depleted, but all mineral deposits are ultimately exhaustible. The tempo of exploration and development should be adjusted to current and future needs for raw materials by industry, and such problems should be studied by a mineral-appraisal group set up in government and co-operating with industry. Even though ultimately research on ore-finding techniques, together with the statistical studies of such a group, enables us to find ore bodies in areas that are now unprospected, the time lag between discovery and production is a neglected factor of vital importance in utilizing newly discovered deposits or reserves already known in mines temporarily shut down.

Under really free enterprise any source of raw materials unable to produce competitively with others should be ruled out, but the mining industry has been subsidized in one form or another for many decades, and it is inconceivable that we should ever again have a really free market. It is essential to the security of the Free World that domestic mining industries be maintained with a dependable labor force in active production. To this end I propose that the United States guarantee a price support for all the durable mineral raw materials essential to industry and accumulate reserve stocks of these raw materials for decades to come. There should be a continuing price support, guaranteed for at least three years in advance. I believe that this would reassure both capital and labor at home and abroad as to the stability of their mining industry. The reserve stocks should in no way be confused with buffer stocks, nor with our military stockpiles which of course should be kept intact and separate from the reserves I propose. Such reserve stocks should be built up continuously until at least equivalent to about five years' consumption. If the rate of accumulation averaged 20 per cent of our national consumption per year the present economy will not be materially disturbed. During periods of depression or business recession the reserves would be built up at a faster rate because of the price support and the diminished consumption of the industrial market. This plan would help bring venture capital back into the mineral industry at home as well as abroad, it would minimize labor troubles and preserve the skilled labor force which is essential to security, and should also remove pressure on both labor and management to ask for high tariffs.

This government-supported market would give dollars to foreign nations in exchange for raw materials and would tend to hold up their economies much as the Marshall plan has done in the past. These reserves would diminish rather than increase international tensions, and its value in terms of security cannot be overestimated. Both its immediate and secondary effects will materially aid in safeguarding the industrial economy of the free world, and could be a vitally important factor for preserving peace and harmony among the family of nations.

CONTENTS

TEXT

	Page
Introduction	103
The major economic systems	104
Free enterprise	104
Controlled economies	105
Characteristics of industrial economies	105
The United States economy since 1800	109
Some economic causes of changing social attitudes	114
The mineral industry	119
Security through a national materials reserve	123
References cited	125

ILLUSTRATIONS

Figure	Page
1.—Selected examples of growth curves in the United States	106
2.—Increase of efficiency in the use of coal	107
3.—Distribution of net national income by industrial classes	109
4.—Consumer credit, personal savings, and unemployment	112
5.—Effect of major wars on the national economy	113
6.—Percentage distribution of wage earners by income, before tax, 1939 and 1949	116
7.—Median wage or salary income per worker by major industry groups, 1939 and 1949	117
8.—Per-capita production of steel in the United States, and U. S. production of steel in millions of short tons	118

Introduction

All of us realize that the mineral industries play an indispensable role in our nation's economy, but usually we are far too busy in some narrow segment of our profession to have time to examine the larger aspects of our ever-changing economic system although it ultimately determines our work, our income, our standard of living, and the security of present and future Americans. The mineral industry is a small but very vital part of this economy and is firmly tied to the manufacturing and construction industries, which in turn are dependent on mineral supplies.

This manufacturing economy of ours has grown great under the free enterprise philosophy. We must face the fact, however, that in the past 25 years our social and economic philosophy has changed radically and that our responsibilities have become those of world leadership. The domestic and foreign problems we face in the not-distant future are interwoven with a fundamental dependence on shifting sources of wasting assets—of minerals for industry. I intend to propose a course of action—perhaps it should be called a change in our national economic philosophy—that will provide a firm foundation for our mineral-dependent economy for many decades to come. Specifically, I shall propose that this country accumulate large quantities of durable industrial raw materials, not as emergency stockpiles, but as reserve stocks comparable in aggregate value to our gold reserves. The primary objectives of this plan are to help stabilize the mining industry at home and abroad, and thereby strengthen the free world economies and to provide us with a powerful instrument designed to minimize international friction and to promote peace.

There is much doctrine and more propaganda in the average article discussing economics today—which too often is written to "make a point" for some particular pressure group and to justify a course of action that may prove inimical to the interests of the majority of the people. This analysis may not be free of these same faults, but, in support of my hope that it is fairly objective in its discussion, I can say that many of my preconceived ideas have been completely changed as I have delved deeper and deeper into the morass of statistics, claims, and counterclaims of various economic groups. Incidentally, I want to make it perfectly plain that, although I am a member of the U. S. Geological Survey, the ideas and opinions I express are definitely my own and do not necessarily either reflect or agree with those of the U. S. Geological Survey, nor with those of the many friends with whom I have had very profitable discussions. I wish, however, to specifically acknowledge the acuminate criticisms given by Mr. James Gilluly, both of manuscript and of ideas. I am also deeply indebted to Mr. Allen Bassett for much help in assembling and graphing statistical information and to Miss Elizabeth Wellshear for some unusually difficult pieces of library research—especially that involved in digging out the data regarding war consumption of steel.

Before considering some of the dangers now visible for our mineral-dependent economy and measures to safeguard it, we should analyze a few obvious and tacit assumptions made concerning the economic framework of our lives, the better to discover its strength and weakness.

The Major Economic Systems

Free Enterprise

Reduced to its simplest terms the fundamental philosophy of free enterprise is that competition, with an absolute minimum of government interference, is the best possible way to achieve the lowest cost, the highest quality, and the largest quantity of any particular goods for the consumer. Implicit in this belief is the assumption that labor competes for jobs and that producers compete for the market. If we pursue the consequences of these assumptions and beliefs we immediately find ourselves in an area of conflict, faced with unpalatable choices. First, if there is to be the competition for jobs necessary to get efficient and dependable labor, we must have a permanent reservoir of temporarily unemployed. Furthermore, the larger the reservoir of unemployed, the greater the competition for jobs, and the higher the degree of efficiency which may be expected from the laborer. The increase in efficiency of labor, as measured in units of output per man hour, was very marked during the Great Depression, and lends this assumption a certain credibility but it discounts the part played by the engineer. We could also consider as a corollary that the higher the unemployment the less security each worker feels in his job tenure and, therefore, the less security the greater the production per capita. To all of which we can answer that there may well be an optimum figure for unemployment and an optimum amount of insecurity to give free enterprise the most satisfactory labor efficiency with the least burden on the economy as a whole.

To maintain competition for markets amongst producers the consumption of goods must be less than the production of goods. This in turn requires that the purchasing capacity of the consumer be less than the potential productive output of the economy if the consumer is to benefit from the fundamental principles that underlie free enterprise. When purchasing power exceeds production, competition shifts from the seller to the buyer and inflation results, unless there is government intervention—the whole idea of which is contrary to the tenets of the free enterprise system.

Are we then to conclude that, to achieve the desideratum of lower costs, better material, and increasing abundance of goods, we should have over-production and high unemployment? There is no doubt but that the greater the over-production the keener the competition amongst the sellers and the lower the cost to the consumer. It is a further corollary that the greater the over-production, the larger the number of business failures that result; therefore, the more business failures per year, the lower the cost to the consumer; and yet few entrepreneurs would choose this as an index of successful free enterprise. It may be noted in passing that this statement of the situation is really quite accurate for those with fixed incomes. The years in the Great Depression when business failures reached the all-time high of over 900 million dollars worth of liabilities per annum saw the largest purchasing power of the dollar, and therefore resulted in achieving for those with fixed incomes the stated objectives of free enterprise: the best, the most, for the least.

In summary, then, we may say that to work most successfully the free enterprise system requires a very delicate adjustment of conflicting interests, an optimum percentage of business failure, an optimum percentage of unemployed, an optimum relation of production to demand and purchasing power. The last is especially hard to keep in balance. The virtue of thrift may suddenly become the vice of hoarding, and the overall effect of savings on an economy is definitely adverse when the uninvested assets start to increase appreciably. If uninvested savings and other withdrawals increase at more than the population growth rate then artificial markets must be found for part of the goods produced if catastrophic unemployment is to be avoided. This was clearly true in the depression of the 30s and during World War II, and brings me to the so-called controlled economy which characterized the war years.

Controlled Economies

Controlled economies are of two very different sorts; the first I would call government-controlled private enterprise and the second government-controlled state enterprise. During World War II the United States went into a government-controlled private enterprise economy. The government rigidly controlled prices, credit, and in a lesser degree purchases, and to a slight extent employment also, but left the individual above draft age relatively free to select his job or to engage in entrepreneureal activities of his own choosing. The purchasing of scarce goods required an elaborate system of priorities which was very irksome to everyone concerned. Government rationing of food was an annoyance that few of us will forget, but an important thing to note is that this system with all its inconvenicenes did prove workable under very difficult circumstances.

Government-controlled state enterprise ranges from the relatively democratic socialism of Great Britain or Sweden to the police state under which the current Communist governments of the world operate. The latter seems to combine the worst features of free enterprise and government-controlled private enterprise with a few peculiar to Oriental despotism, but in theory, at least, it has one or two of the better features that marked government control of private enterprise. It started with the Marxist assumption that all workers were equal and the logical deduction that all in the labor force should therefore receive the same compensation. This assumption soon proved quite unworkable, and by the late 1930s there was already a greater discrepancy between the lowest and highest annual take-home pay of Soviet workers than of those in the United States labor force,—and I include the so-called captains of industry in our labor force; a very few nonwage entrepreneurs undoubtedly exceeded this.

It is of course difficult to speak objectively of the controlled state enterprise economy of the Communist type because of the interrelation of Communist ideology which in its many vicious precepts and practices is utterly repugnant to me. Fixing our attention on the economy alone, however, it may be said that, in contrast with free enterprise, the government itself determines quality, quantity, wages, profits, prices, kind of merchandise, and its distribution. Two things can be said for the Communist type economy on the credit side, however. The first is that it has kept going for more than 30 years in spite of predictions to the contrary. The second is that it permits planning for national objectives and, in theory, the utilization of the nation's resources to the best advantage for both long-range and short-range needs. Against this, however, we must place the difficulty of providing a strong incentive to produce more, better, cheaper; the supposedly greater problem of getting efficiency in government-controlled industries; the lack of freedom of labor to bargain with its employer; and the determination of kind, quality, and quantity of goods by bureaucrats rather than by consumer demand. The intelligent integration of the labor force in a planned economy *may* be responsible for the continuing steep growth curves of industry in the U.S.S.R., as the Communists believe, but almost any type of industrial economy would operate successfully given the resources and internal market enjoyed currently by the U.S.S.R.

Characteristics of Industrial Economies

Regardless of the philosophy governing the various industrial economies of the world, they have several characteristics in common, to some of which I wish to direct attention.

They all comprise dynamic rather than static factors; the industries of which they are composed show definite patterns of growth,—sigmoid curves where output is plotted against time. In recent years much has been written on the characteristics of industrial growth curves, all of which belong to that general mathematical group known as logistic curves. Typical of them is the so-called Gompertz growth curve frequently used to compute the expected general changes in individual industries (National Industrial Conference Board, 1952). A few selected examples of growth curves are shown in Figure 1 to emphasize the characteristics of some major components in our own economy and to suggest the type of change that takes place in all industrial economies.

The characteristic of the growth curves shown in Figure 1 on which to fix our attention is the change in rate of growth as measured by the annual percentage increase, not the numerical

The motor-vehicle industry at first expanded phenomenally, but by 1950 its growth rate had dropped to slightly more than 1 per cent per annum, not much more than the rate of

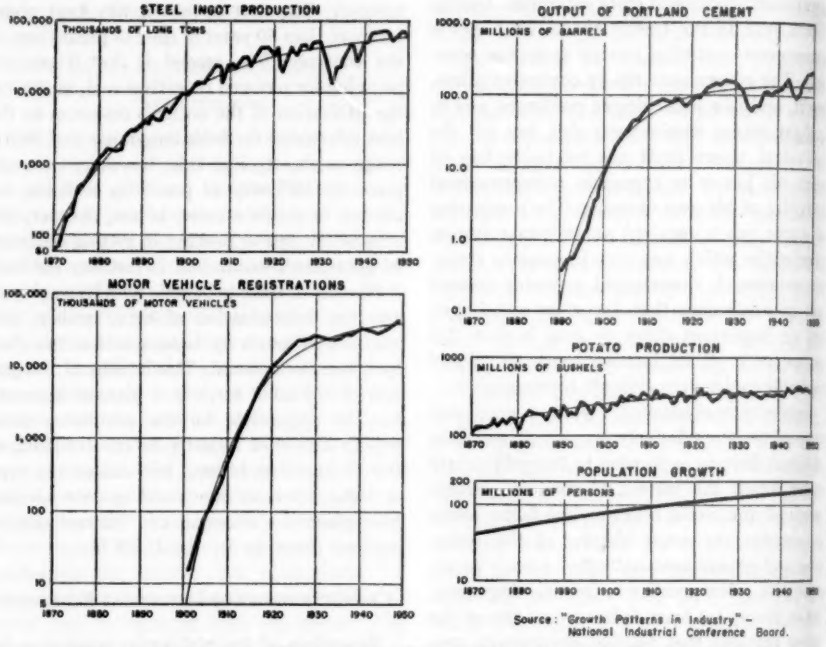


FIGURE 1.—SELECTED EXAMPLES OF GROWTH CURVES IN THE UNITED STATES

Showing: Steel Ingot Production, Output of Portland Cement, Motor Vehicle Registrations, Potato Production, and Population Growth in the United States.

change from year to year. In every instance, after the burgeoning of an industry the rate of increase holds steady for some time and then drops rapidly. For example, steel production prior to 1917 increased at about 4 per cent per annum, but the rate has since fallen until now the trend is upward at only a little more than 1.0 per cent, and, though a sharp increase in steel production may be expected because of government demand, annual production would probably fall far below 100 million tons if the government supported market weakened (Fig. 8). Similarly the output of Portland Cement was rising at the rate of 10½ per cent per annum until about 1909 when the rate dropped sharply; by 1951 it had fallen to approximately 0.2 per cent per year.

population increase in the United States. The flattening of industrial growth curves reflects with clarity the change in the normal (non-government) consumer market after the initial demand is satisfied. Food production should parallel population growth, and, as illustrative of food commodities, potato production in the United States shows a growth rate through the years directly comparable to that of the population.

The efficiency of machines also shows a growth curve and one that has a definite limit imposed by physical laws. The increased output per worker during the past several decades has been largely brought about by the engineers who have designed more and more efficient machines, rather than by the increased skill

or diligence of the laborer. The new equipment, however, may demand greater attention and a higher order of ability in the operator than did the mediums replaced. Ultimately, in spite of

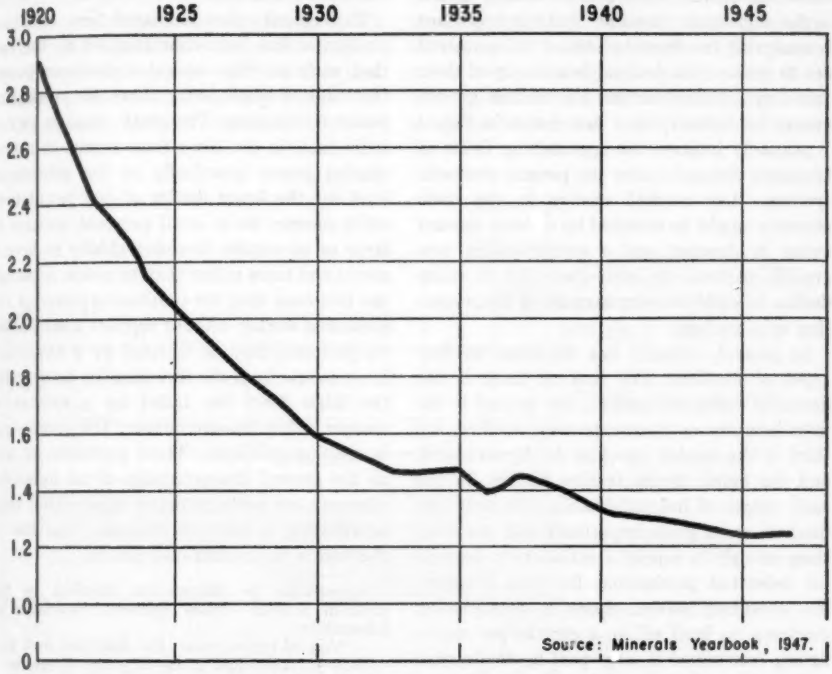


FIGURE 2.—INCREASE OF EFFICIENCY IN THE USE OF COAL

Showing: Electric power in pounds of coal per kilowatt-hour (Central Stations).

engineering, the decreasing costs (and the per capita output) in industry must level off, but we are still far from approaching the ultimate limit in machine efficiency in some industries. The consumption of coal per kilowatt hour in electrical plants, on the other hand, clearly indicates the approach of top efficiency for the present type of equipment, and this is characteristic of the changes to be expected in the industrial era (Fig. 2).

If the trends now apparently well established in the United States continue, we will see in the not distant future both a leveling off in the efficiency of machines and in the demand per capita. "Industry" is a summation of its industries; it therefore seems logical that the growth curve of the total industrial output should flatten—unless some substantial change in our economy takes place. In this conclusion I differ with the outlook expressed by the President's Materials Policy Commission (1952, p. 3) which "assumes no more than that the nation's economy will continue to grow at about the rate it has grown during the most recent one hundred years of economic activity."

It is to be expected that in our country agricultural production will closely parallel the growth rate of the population, if surpluses and deficiencies are avoided. The domestic consumer demand can fluctuate little, and, regardless of purchasing power, agricultural

products will hold first priority on the consumer's income. The manufacturing industry, on the other hand, is powered by the twin engines of consumer purchasing power and consumer desires. These two are usually united in the single term "demand," but it is important in analyzing the characteristics of the industrial era to realize that demand is made up of these two very different factors. The various growth curves for industry that are shown in Figure 1 primarily indicate the approaching limits of consumer demand under the present economic systems. Any marked change in the basic economy might be reflected by a sharp upward swing in demand and a corresponding new growth pattern, or conversely by a sharp decline in some industry because of the restriction of a market.

In general, industry has depended on four types of markets: The first of these is the domestic consumer market, the second is the inter-industry or plant-expansion market, the third is the market provided by Government, and the fourth is the foreign market. In the early stages of industrialization, the first two markets are of prime importance and are more than enough to supply a satisfactory demand for industrial production. In time, however, the consumer market shows a disconcerting tendency to level off at a certain per capita figure, determined in large part by the median wage paid to the industrial worker, not by the satisfaction of his desire for goods (Figs. 1, 7).

For more than a century and a half one of the most striking characteristics of the industrial era has been the multiplication of production by machinery. This is aptly illustrated by a statement in Mulhull's Dictionary of Statistics for 1889 (p. 365):

> "A girl twelve years of age in a Lancashire mill can turn out 35 yards of printed calico daily, her work in one year sufficing to clothe yearly 1200 persons in the East."

This illustration is cited because I wish to emphasize two important factors: The child's wages, which probably amounted to less than 25 cents a day,[1] were far less than the value she added to the raw materials by her labor,[2] and second, when considered in relation to present political and social attitudes, it emphasizes the amount and the direction of change in our economic mores.

Throughout the industrial era machine production has been characterized by the fact that each machine operator produces goods the value of which is far above his purchasing power to consume. The great range in pay of individuals in the labor force results in a purchasing power practically at the subsistence level for the lower deciles of our population, while income for a small per cent remains so large as to require diversion chiefly to investments and taxes rather than to goods. Although the inference that the purchasing power of the industrial worker will not support a market for his products may be debated by a few, there is no escape from the fact that for many years the labor force has failed by a substantial margin to buy its own output. This poses some interesting problems. These problems as well as the general characteristics of an industrial economy are perhaps better appreciated after scrutinizing a relevant example. And one of the best is that of our own nation.

[1] In the early 1890s a similar laborer received from 1½ to 4 cents per hour in the United States (Wright, 1894).

[2] According to information supplied by the Oldham Master Cotton Spinners Association of Lancashire:

"Age of employment. For *half-time* work in 1889 juveniles had to be 10 years of age (increased in 1893 to 11). For full-time work juveniles had to be 13 years of age, and must have attained a certain standard of education (calculated mainly by number of school attendances), otherwise they had to be 14 years of age.

"Hours of work (full-time). 56½ hours. Weekdays 6 a.m.–6 p.m. with 2 hours for meals, Saturdays 6 a.m.–1 p.m. with ½ hour for meal.

"Wages. Varied with the type of 'mule.' A junior newly working *full-time* would earn approximately 8 shillings per week. On weft mules, which were larger, he could earn up to 13 shillings.

"A *half-timer* would get about half a full-timer's earnings, and probably not more than 5 shillings per week."

Cotton cost £2 per bale in England in 1889, or approximately 2 cents per pound; the printed calico made from raw cotton in these Lancashire mills was valued at £5 per 100 yards or about 25 cents per yard; 35 yards of calico weighs about 7 pounds, and thus the labor and raw materials for the 35 yards of printed calico would be well under 50 cents as contrasted with the value of $8.75 for the finished product of a day of child labor in the Lancashire of 1889 (Mulhull's Dictionary of Statistics, 1892, p. 482).

THE UNITED STATES ECONOMY SINCE 1800

The chart shown in Figure 3 gives a graphic summary of the development of the United States into a virtually self-sufficient industrial nation from the dominantly agrarian nation it was 150 years ago. It does not, however, portray the economic stresses and strains that accompanied the change, nor does it show the vast increase in national wealth and in our standard of living during this period. In 1800 nearly 40 per cent of our entire national income came from agriculture and related industries, 12 per cent from manufacturing, and only 0.1 per cent from our mineral industries; a century and a half later agriculture contributed only 13 per cent, but industry accounted for a third of our national income, and the mineral industries are credited with 6 per cent.

For 150 years the aggregate contribution of agriculture, the mineral industries, and manufacturing has approximated 50 per cent of the total net national income and probably will remain at least this high if our standard of living is maintained. Trade and non-government service usually contribute approximately 30 per cent of the national income, and it is worthy of note that as this percentage increases the economy as a whole suffers; its maxima clearly correspond to business recessions. The wages and salary paid to government workers, both military and nonmilitary is properly allocated to the service segment of our economy, though they are usually excluded from consideration in discussions of national income, but see Figure 3. Prior to 1929 the sum paid during peace time to workers for state, local, and county governments was approximately five times that paid to all federal employees—both military and civilian. After 1930 the ratio of the two steadily decreased, and during World War II the number of civilian federal employees equalled that for state, local, and municipal governments, and the ratio has remained approximately one to one for the seven years 1946–1952. In 1929 the total income of all government employees—

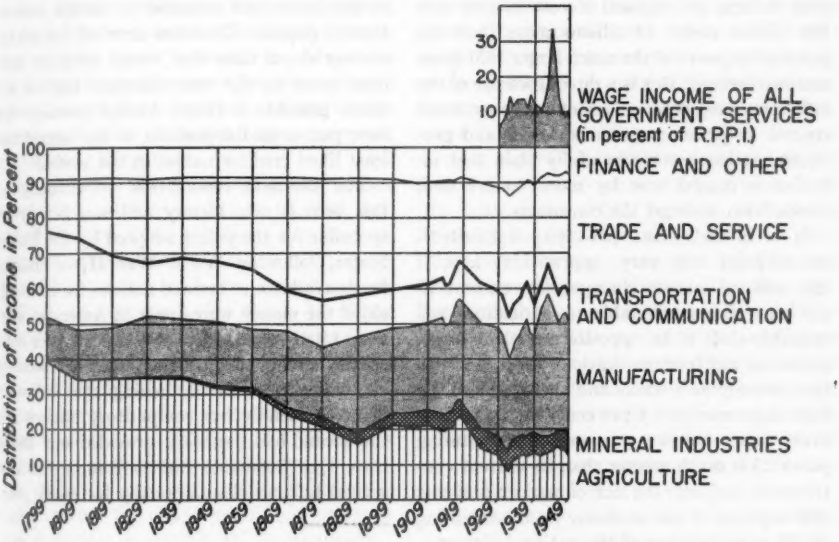


FIGURE 3.—DISTRIBUTION OF NET NATIONAL INCOME BY INDUSTRIAL CLASSES
(Realized Private Production Income)

Showing: Finance and other, Trade and Service, Transportation and Communication, Manufacturing, Mineral Industries, and Agriculture.

federal, state, county, and local—amounted to 5½ per cent of the national income; in 1949 the percentage had risen to 9.

The increase in government payrolls during World War II required to administer a government-controlled private enterprise system was actually a far smaller cost to the consumer than the decrease in purchasing power of the dollar since the close of the war. Because of inflation the gross national income of 240 billion dollars in 1951 was equivalent to about 140 billion 1945 dollars; the national income in 1945 was 180 billion, about 40 billions more than the purchasing power of the much larger 1951 gross national income. This is a direct measure of the inflation consequent on removing government control on prices, consumers, labor, and producers. It has become painfully plain that inflation is caused now by more factors than competition amongst the consumers.

It is unlikely that per-capita agricultural consumption will vary appreciably, and, if the national income changes, the current 13 per cent now attributable to agriculture will probably shift in an opposite direction; transportation and communications fluctuate with the economy as a whole and should shift little from approximately 8 per cent. There is, however, clear evidence that our manufacturing potential is much greater than its current contribution, and only the lack of markets prevents this segment of our economy from accounting for 35 or 40 per cent of the national income.

In the early part of our history, then, products of agriculture dominated both our domestic and our export markets, but near the latter half of the nineteenth century the United States shifted gradually, but irretrievably, from an agricultural to an industrial economy.

During the rapid growth of many new manufacturing and mining industries, the normal demand of the inter-industry market and the personal consumer market sufficed us; net export foreign markets and artificial government-supported markets consumed a negligible part of our gross national products. The percentage rate of increase of our major industries first began to drop perceptibly during the 1920s as the early widespread domestic demand for products of the industrial era slackened under the impact of production-line methods. Within a decade it had dwindled to relatively uniform per-capita requirements. In spite of this our industrial plant has continued to grow enormously with only a temporary setback in the early 30s. The weakened personal consumer market has been offset so far by our growing artificial markets.

This development in our current economy seems to have started as an aftermath of World War I when private and government lending to the devastated countries in Europe was extremely popular. The loans drew off the surplus savings above those that would normally have been spent on our own consumer market and made possible a strong foreign market—but soon put us in the position of the largest and least liked creditor nation in the world.[3]

The ultimate repudiation of virtually all this debt is now history and was largely responsible for the policy adopted by the United States, following World War II, of making funds available to favored nations for economic aid if the money were spent in American markets. Little or no return was expected for most of this money except the increased security we enjoy from strengthening the industrial plant of friendly but competitory nations and the second-hand subsidy provided our industries. Our Economic Aid to Europe has cost several billion dollars annually for many years

[3] The Dawes Plan re-established Germany's credit, at least in the United States, and made that bond market popular. German bonds bought by Americans approximately equalled the total German reparation payments, which from the inception of the Dawes Plan to the Hoover moratorium of 1931 amounted to $2,584,870,400 (Hodgson, 1932, p. 212). The best available figures show that the total of American long-term loans and short-term credits to Germany was about $2,705,490,000 in 1931. In other words, it would seem that Germany paid France, England, and other allied countries, except the United States, only what the American bank investors paid in. The total obligations of foreign governments held by the United States Government at the end of 1929 amounted to about 11.5 billion dollars, but the short-term and long-term credits held by American investors in European paper was approximately 7 billion dollars at this time. It is presumed that much of the 18 billion dollars sent abroad was used to buy American goods, and certainly it did much to hold up the market for exports of industrial equipment during the decade preceding the depression.

and has supported an artificial or "negative" market that takes an appreciable percentage of our gross national product.

Another type of artificial market maintained by the Federal government is that of outright subsidy to groups that are important either because of political pressures or because of security and economic factors. In this category belong such things as parity farm prices and the essential, but indirect, subsidy paid to commercial aviation through the Civil Aeronautics Administration services in maintaining air fields, beacons, and the like, as well as the direct subsidy for air mail; also the substantial aid accorded our Merchant Marine to enable them to meet the competition of the foreign merchant marine which has lower wages and consequently lower costs.

By all odds the most substantial direct government subsidy market is the one supported by the relatively high sum paid to veterans, approximately 5 billion dollars per year. This together with the interest on our national debt accounts for about 11 billion dollars a year of federal spending. When European Aid, price supports, and other similar subsidies are added, the sum allocated to the direct support of artificial markets—past and present—costs annually about 18 to 20 billions exclusive of all military expenditures.

A somewhat dangerous artificial market is easily created by credit expansion, which in turn is largely controlled by Federal policy. Consumer credit, like personal savings, has little effect on the economy so long as it remains relatively static, but when it expands at the rate of billions of dollars per annum for several years it creates an artificially supported market which could blow up in our faces when credit is again restricted, as witness the Great Depression of the 30s.

The relation of consumer credit, personal savings, and unemployment is shown in Figure 4, and this chart is worthy of some study, bearing in mind the artificial markets that have been supported by the government since World War II. In 1945 the backlog of personal savings was at its highest figure in more than a quarter of a century (U. S. Dept. Commerce, 1951, p. 152) and reflected the earnings dammed up by tight government controls on consumer goods markets during the war and the diversion of industrial capacity to the artificial market created by war-time needs. The increase in unemployment from 1 million in 1945 to 2 million in 1946 is surprisingly small when we consider the large number of men turned loose from the army during the latter part of 1945 and in 1946. Unemployment remained relatively stationary for three years and then began to rise sharply, reaching a peak in mid-1950 when the Korean war broke out. The remarkably rapid drop in personal savings through 1946 and 1947 indicates that consumer demand was exploited to virtually the full capacity of the personal consumer market, and the increase in unemployment in 1949 and 1950 suggests that even the backlog of personal savings accumulated during World War II was nearly used up by most of the labor force within the first three years following the war. It is further worthy of note that, even with the government subsidies and artificial markets maintained through price supports and Economic Cooperation Administration, industrial production was insufficient to keep unemployment from doubling in less than 14 months. This increase in unemployment was largely in the durable goods manufacturing industries and showed a ratio of about two to one relative to unemployment in nondurable goods.

It is not surprising therefore, with the sudden increase in plant expansion necessitated by the Korean war, together with the consumer "scare-buying" demand, that unemployment should drop off rapidly and that our gross national product should continue to increase through 1951 and 1952. Without the psychological effect of the Korean war and the artificial market created by the heavy government demand for armaments, I see nothing within the current operation of the free enterprise economy that would have changed the trend toward increasing unemployment. Because of the political power of labor at the present time and because the distribution of national income is ultimately in the hands of our political representatives, it seems most probable that, even without the Korean "Police Action," government economic intervention would have come

about in some form well before the close of 1952.

The market supported directly by our National Government has fluctuated tremendously in the past century and a half, and its varying importance in the national economy is reflected by the changes in the national debt, which show a conspicuous correlation with wars and times of crises (Fig. 5). If we consider only the wars we note some interesting increases in the national debt:

The War of 1812	$140,000,000
The Civil War	2,500,000,000
World War I	25,000,000,000
World War II	250,000,000,000

Following each war there was a temporary decrease in the debt, but it is worthy of note that each of our major wars has seen an increase, by a factor of about ten, in the national debt over that incurred for the preceding war.

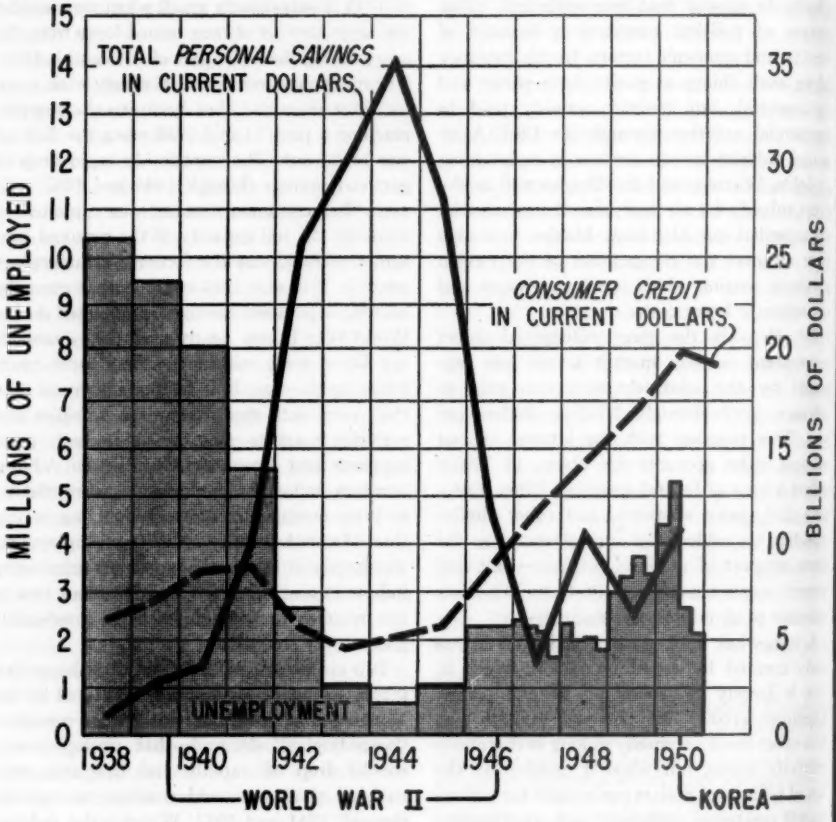


FIGURE 4.—CONSUMER CREDIT, PERSONAL SAVINGS, AND UNEMPLOYMENT
Source: Dept. of Commerce, National Income Supplement to Survey.

Prior to the Great Depression of the early 1930s the government was a heavy, but intermittent, buyer, and the heavy buying was confined to times of "hot" wars. Beginning in the 1930s, however, a different pattern became evident—that of a growing intervention in the national market during periods of peace-time economic crisis, as well as in time of declared war.

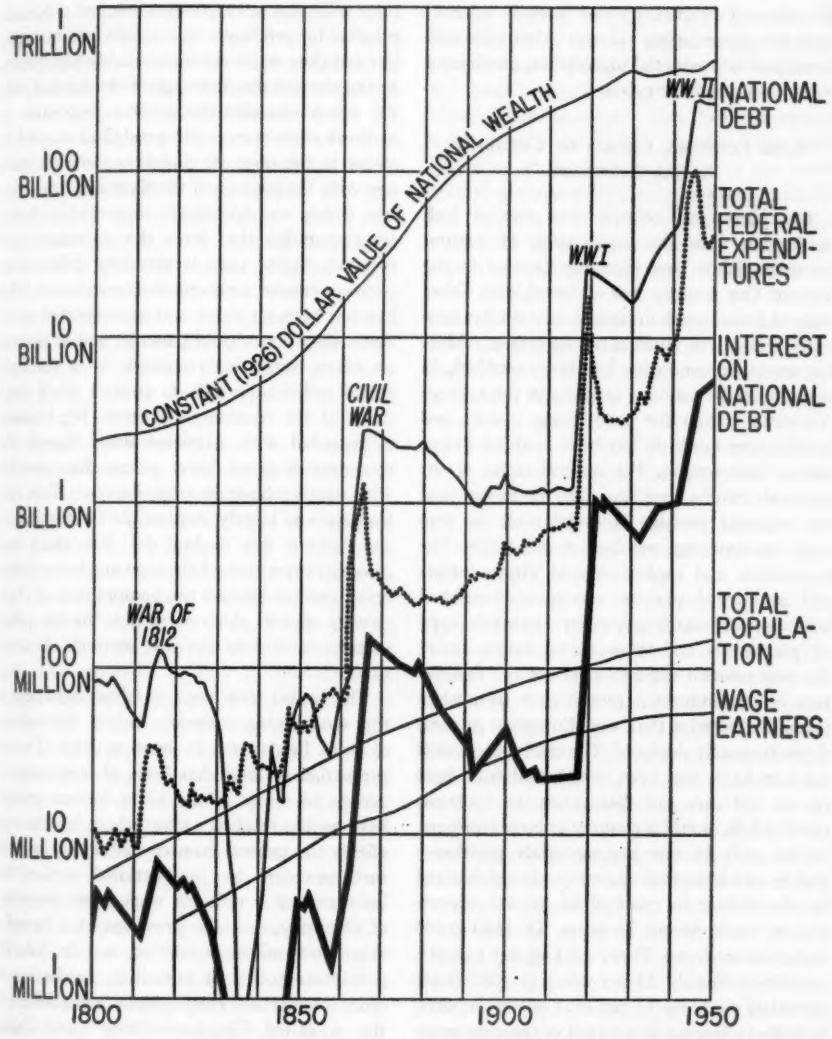


FIGURE 5.—EFFECT OF MAJOR WARS ON THE NATIONAL ECONOMY

Showing: National Debt, Total Federal Expenditures, Interest on the National Debt, Total Population, and Wage Earner Population, and Value of National Wealth in Constant (1926) Dollars. Data from *Historical Statistics of the United States* and *Statistical Abstracts of the United States.*

Military and security expenditures fluctuate enormously (12 billion in 1950, 40 billion in 1952) but have been the largest single item of expenditure by the government for more than a decade, and have provided our contradictory economy with a market that has been a major factor in holding production and employment at high levels. We hope, however, that eventually the price of security will diminish, and I look forward to the time when we again will be faced with the same old problem, what to do with the excess of productive capacity above

the demand created by our normal internal market—remembering always that demand consists of two essential ingredients, purchasing power and desire for goods.

Some Economic Causes of Changing Social Attitudes

The nineteenth century was one of lush production with the exploitation of natural resources, labor, and ingenuity pushed to the utmost. Our country was endowed with richer natural treasures than almost any similar area in the world. Too much of our success in achieving world pre-eminence has been ascribed, in my opinion, to a unique capacity in the average American citizen for hard work, vision, and intelligence; too little has been credited to our natural endowment. The upward curve of our national income, our standard of living, and our national prestige is correlatable in part with an amazing number of windfalls. The acquisition and exploitation of virgin forests and untouched prairies enormously enriched our westward-moving frontier—but this type of plunder is not there to be taken again; the vast mineral deposits that are the foundation of our industrial power were untouched through centuries that saw European mineral deposits greatly depleted. The easily discovered deposits have now been found, and from here on we will earn our discoveries. In contrast, the U.S.S.R. is still a country of large frontiers.

The shift in our raw-materials position—and in our industrial economy—is emphasized by the change in composition of our export-import trade during 75 years. In 1880 crude materials made up 70 per cent of our exports, in 1946–1950 only 25 per cent; in 1880 crude materials made up 12 per cent of our imports, in 1946–1950 some 53 per cent of the very much greater volume (President's Materials Policy Commission, 1952, p. 16).

The general principles underlying our early laissez faire economy worked strongly in favor of the producers and of the fixed-income class during the nineteenth-century period of industrial expansion. Our economy was little hampered by social conscience. Labor was virtually unprotected from ruthless exploitation. Not only was the competition in the labor force sufficient to keep wages low, but it became possible for producers to combine into monopolies and thus maintain unreasonably high prices, to the obvious disadvantage of the general public, which was also the general electorate. As a direct consequence the pendulum started to swing in the opposite direction some 60 years ago with the passage of the Sherman Anti-trust law which was specifically intended to break up monopolies that force the consumer price of goods higher than it would be if free competition existed amongst these producers. This law has been amended and reinterpreted many times since its original passage, and at present its effect, surprisingly enough, is to maintain prices sufficiently high to protect small business—at the consumer's expense. Big business is regarded with suspicion even though the consumer is given lower prices than possible with smaller business organizations. This philosophy was largely responsible for the Robinson-Patman Act during the 30s which was designed to protect wholesalers and independent retail grocers against the competition of chain grocery stores which were able to cut prices because of efficient low-cost methods of operation.

The brutal treatment of labor, especially in the coal-mining industry before the advent of John Lewis, was an open scandal. The organization of labor has been of immeasurable benefit to many of the lower income groups, but now has reached a stage where it frequently affects the general economy adversely through such practices as jurisdictional strikes, the insistence of a uniform wage scale regardless of efficiency, and the provision that seniority alone determines promotion on the job. Its pernicious policy of curtailing production in order to increase employment has resulted in the so-called "feather-bedding" and "slow-down" which are both a disgrace and a challenge to our present economy. The conflict between labor and management, though far less bitter than formerly, has grown ever more damaging to the interests of the weakly organized white collar worker. Both labor and capital control production, and each is therefore in a position of power.

During the 1920s the farmers began to realize—perhaps subconsciously—that the distribu-

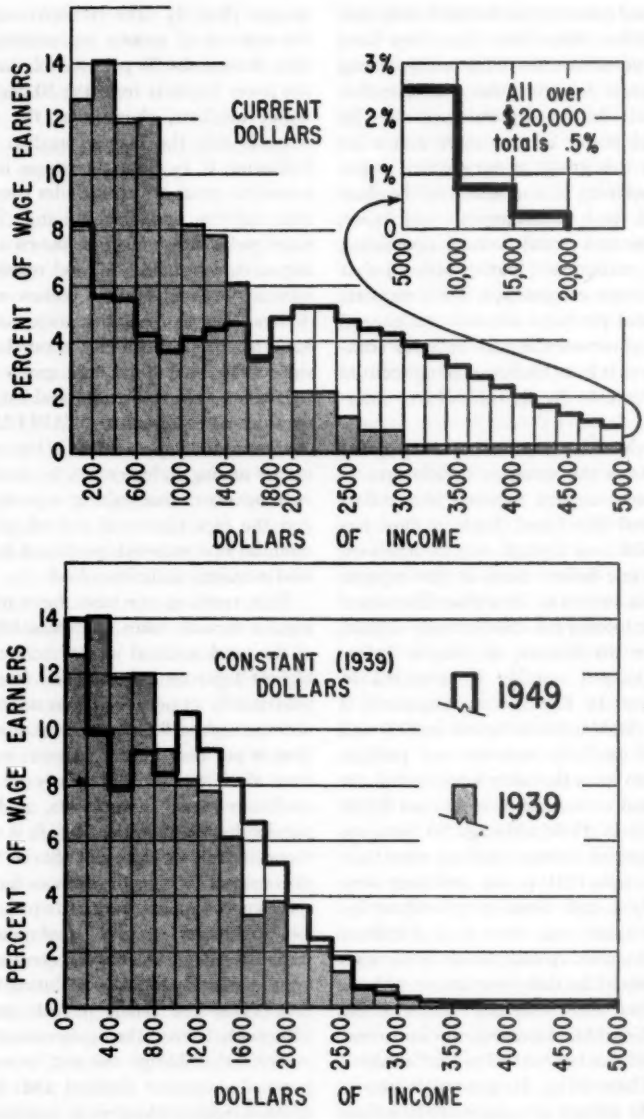
tion of national income is in the final analysis a political decision. Since that time they have consistently voted in a way that brings strong political pressure for government intervention in their behalf. In the depression of the 30s their political power became more and more evident, and this group of agricultural entrepreneurs, combining in a unique way the characteristics of both management and labor, began the modern trend toward demanding government guarantees ("parity prices") that would contravene competition. Price supports for agricultural products are now an integral part of our governmental and national economy, and there is little likelihood of agriculture again going back to the old rules of free enterprise.

For approximately 20 years the white collar worker has been the unhappy middle man in a three-cornered conflict between blue collar, blue jeans, and blue blood. Each of these has been successful in a limited way in achieving a higher income before taxes at the expense of a pernicious anemia of the dollar. The actual value of their income has changed only a little, although the distribution of income before taxes has changed notably if measured in current dollars. In Figure 6 a comparison is made of the distribution of income in 1939 and 1949. It will probably interest and perhaps surprise you to learn that only 4 per cent of the labor force had an income of more than $5000 (before taxes) in 1949, although 10 per cent of all who received income received more than $5700 (Weintraub, 1951, p. 64), and there were approximately a half dozen people whose income before taxes was more than 5 million dollars in that year. A comparison of incomes after taxes would be definitely unfavorable to the 1949 labor take-home pay. Most of the increase in the middle income group in current dollars in 1949 can be ascribed to the "success" of collective bargaining. Its general failure in terms of 1939 dollars or even in 1945 dollars was due to inflation caused in no small part by this same success in collective bargaining.

That some groups have been successful in raising their income and that the higher income brackets have been somewhat less successful are indicated by the chart showing the median wage or salary income of the major industrial groups (Fig. 7). The median wage—that is, the amount of money representing the wage that divides the 50 per cent of the workers in the lower brackets from the 50 per cent in the upper brackets, shows that the government wage is still the highest median wage paid. Following it in close succession is the transportation group which includes communication and utilities, and then mining. The median wage paid in mining has shown the greatest improvement since 1939 and represents a real increase both in current dollars and in 1939 dollars. The government wage on the other hand has dropped slightly in purchasing power since 1939. So too has that group represented by finance, insurance, and real estate, usually regarded as representing "CAPITAL."

Most of the improvement in the median wage of the mining industry can be credited to the well-unionized coal mining and oil industries and the fact that coal and oil are the most essential raw materials produced in our industrial economy aside from food.

That tenth of our labor force receiving the highest income takes approximately one-third of the total national income before taxes. The highest 1 per cent of the labor force takes approximately 11 per cent of our national income, and the highest 0.5 per cent takes a little more than 8 per cent of the national income. It is from these groups that nearly all capital for credits, venture investments, and plant expansion has come in the past. It is chiefly from them that the Government obtains money both as taxes and loans, with which to finance deficit spending to support markets to provide demand for production to give employment to the tragically idle masses of competent workers during a depression. And even during boom times their taxes and bonds provide much of the wherewithal for the government-supported markets that bridge the gap between normal personal consumer demand and the high industrial output required to maintain full employment. Compared with the sums spent for security and artificial markets, the money used for other government services is small. Most of the savings wrought by congressmen outside these major items are made usually for political propaganda rather than for motives of real economy. But, sad to say, the loss of



Source: Statistical Abstract of the United States, 1951, p. 275.

FIGURE 6.—PERCENTAGE DISTRIBUTION OF WAGE EARNERS BY INCOME, BEFORE TAX, 1939 AND 1949
Contains two charts, one in current dollars, the other in constant (1939) dollars.

such markets supported by gigantic public funds would cause a chaotic dislocation of our economy. I am forced to the conclusion that we should expect changes but not diminution in our artificial markets. The reason for this view is vividly shown in what at first glance

seems to be a prosaic-looking chart, one showing the ups and downs of the steel industry—but the steel industry is one of our most sensitive industrial barometers (Fig. 8).

leveled off years ago between 700 and 800 pounds per capita and may remain under 800 pounds for years to come. The per-capita steel production is by and large a pretty good index

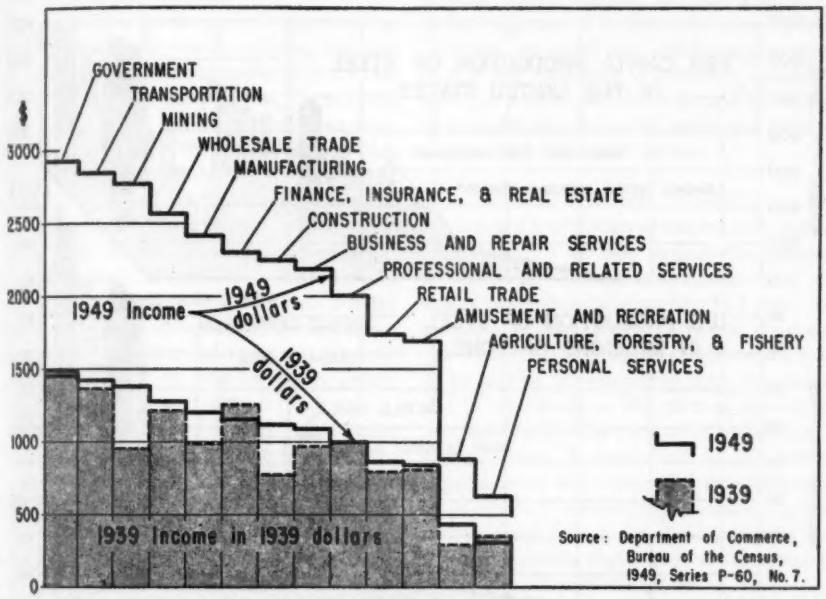


FIGURE 7.—MEDIAN WAGE OR SALARY INCOME PER WORKER BY MAJOR INDUSTRY GROUPS, 1939 AND 1949

Steel capacity and steel production are properly regarded as indicative of the industrial maturity and current industrial health respectively of the nation. The steel production per capita in the United States has exceeded the "normal" labor force consumption for nearly 30 years and if the artificial markets that sustain it were withdrawn we should expect a rapid drop in consumption.[4]

The up-and-down line of per-capita steel output shows a continuing overall increase through the years, but as shown in Figure 8 this is due to the demand created by artificial and negative markets (those that lessen the real national wealth); the markets dependent on unsubsidized consumer demand probably

of industrial activity; when it drops, hard times are here; when it rises, wages rise, employment leaps up, and business booms. The per-capita steel output for the years of full employment and high industrial activity is on a curve that is still rising. Apparently, then, our per-capita output must continue to increase if we are to give full employment to our labor force and enjoy the fruits of high industrial activity—unless some fundamental change takes place in the character of our industrial matrix.

The direction that our economy moves is clearly indicated by the forecasts of steel production made in 1947 by men with different viewpoints. Leaders of the steel industry, steeped in the hard-headed philosophy of our free enterprise system, made forecasts based on a nearly constant per-capita consumer demand; government economists steeped in "New Deal" and "Fair Deal" social philosophy

[4] The material for this section and for Figure 8 comes from American Iron and Steel Institute, Baruch (1921), Clarkson (1923), Hook (1951), Keyserling Report (1952), Mineral Industry, Mineral Yearbook, Steel Yearbook for 1952, War Production Board (1945), and Wheildon (1947).

made forecasts on the bland assumption that full employment *must* be maintained regardless of domestic consumer demand (Wheildon, 1947, p. 277). Our industrial leaders concluded and that the challenge to our free enterprise system cannot be dodged much longer by depending on the struthionic "common sense" of our current crop of industrial and political

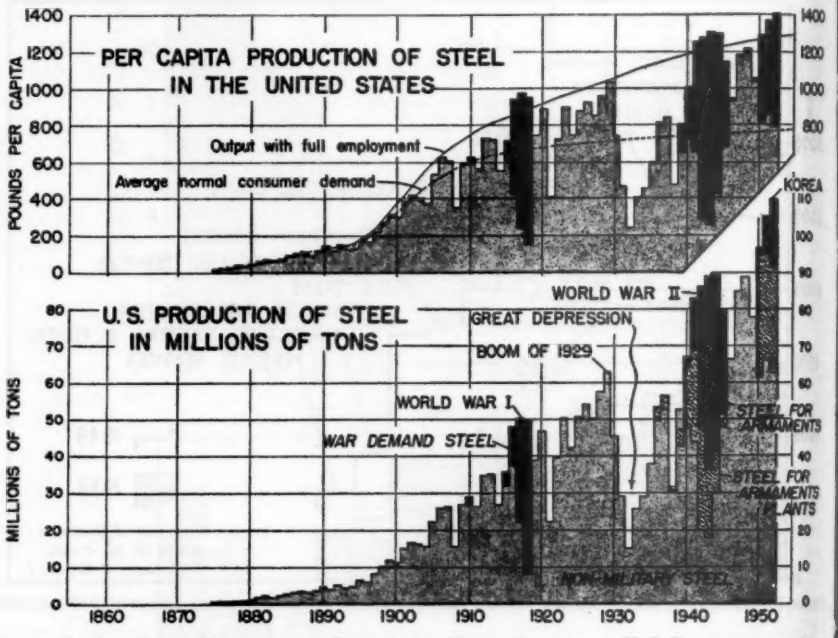


FIGURE 8.—PER-CAPITA PRODUCTION OF STEEL IN THE UNITED STATES, AND U. S. PRODUCTION OF STEEL IN MILLIONS OF SHORT TONS

Showing amounts used in armaments and armament plants, the average output with full employment, and the average normal unsubsidized consumer demand.

that the average consumption was about 700 pounds per capita and that peak consumption would not exceed 980 pounds per capita, assumptions that led to the statement that a peak consumption of 63 million tons would be a maximum for 1950; the government economists forecast that we would require 100 million tons by 1950. And we actually produced 97 million tons.

The steadily increasing divergence of the curves shown in Figure 8 for per-capita consumer demand and per capita consumption for full employment is one of the most startling facts that has come to my attention in many years. *Consumer employment—not consumer demand*—is now determining our output.

I believe that the direction we follow is clear leaders. The voting majority of the labor force will insist on measures leading to full employment; the ever-widening spread between consumer demand per capita and the total steel output per capita accompanying full-scale industrial activity is clearly evident, and the implications of this spread are political and economic dynamite.

Our major problem remains—the bald fact that our labor force can produce much more than its wages buy with the present distribution of income, a distribution that has not changed greatly percentagewise before taxes in 50 years. Business seems to be making frantic efforts to enlarge its markets while ignoring the major problem. I am confident that something constructive can be done, and look forward to the

day when our industrial leaders do other than make stentorian demands for lower taxes and more reasonable wages—while industry becomes more and more dependent on government support of its markets.

Internal markets in general represent an increase in national wealth, whereas the support of foreign markets by subsidies is a drain of either funds or material goods. The artificial market provided by credit expansion is a stimulant that tends to be habit-forming, and it is loaded with a "morning-after" hangover. It is possible, however, that government controls of credit can be relaxed with a minimum of migraines by creating an internal market for construction work of many sorts, most of which result in additions to our national wealth. Before the problem of equating our productive capacity to our labor force income is satisfactorily solved there will be much deficit spending for government projects.

When our next major unemployment problem arises I hope that every effort will be bent toward preventing the same unhappy solution of it—Government doles and government projects at subsistence wages—advocated during the early 30s. There are various alternatives: The purchasing *power* of the lower income groups can be increased by incentive production, by deflation, or by redistribution of national income; the income of some selected groups may be changed by legislation; credit buying can be tried with fleeting success, but when restricted it may precipitate the crisis that it was designed to avoid; exports to creditor nations would help—but we have almost no creditor nations; plant expansion and retooling would also help but would normally proceed at a much diminished rate in the future; the negative markets of armament and free foreign aid are regrettably an expedient likely to be used; and there are public works such as highways, housing, and construction of parks, recreation facilities, and public buildings. This last has the virtue of adding to our national wealth rather than diminishing it as do most artificial markets. This is also true of the possibility, which I shall soon discuss, of building up large reserve stocks of durable raw materials.

The new social and political attitudes adopted in the 1930s will long continue to have a profound effect on our way of life, and our dynamic economy is perhaps on the eve of changes still more drastic than those of recent years. Some of these changes may be directly related to the growing strain imposed on our mineral industry. Certain it is that this same mineral industry, on which our manufacturing plant is so utterly dependent, is witnessing a constant and irreversible shift in its sources of supply, with consequent economic, social, and political problems of world-wide import.

The Mineral Industry

With this brief review of the economic framework in which we now struggle for existence I turn to the mineral industry—the *sine qua non* of our industrial economy. If I were presenting a detailed analysis of the role of mineral raw materials in our economy, much would have to be said of the relation of price to product and to substitutes, of the effect of scarcity, of problems peculiar to each of several types of raw materials; I regret that in the present paper most of these interesting questions must be passed over with scarcely a glance. Instead, I shall touch only a few basic problems and will then suggest a way to maintain an adequate resources position in the future.

We are well aware that mineral deposits are a wasting asset and that in general the longer a deposit is worked the higher the cost of production. Furthermore, practically all concede that the obvious large mineral deposits in the United States have been found—as well as many that are not obvious. From now on the cost of discovering new deposits here will increase sharply, whereas in many underdeveloped areas of the world the costs of discovering, developing and exploiting large deposits will remain much less.

The problem of exploration and development can be considered with respect to several related but separate stages of work. There is the initial exploration or prospecting that leads to the discovery of mineralized ground. This is followed by the proving stage, during which the size, grade, character, and spatial disposition of the mineral deposit is well enough ascertained to allow decision as to the desirability of further work. If the proving stage is encouraging, the development stage is entered, and the deposit is made ready for commercial

exploitation. This stage merges gradually with that of actual production when the property starts shipping its mineral product to the market.

The cost of making the initial discovery is in general far less than that of proving and development.

According to J. A. White (1951, p. 1608), secretary of the National Minerals Advisory Council, about 90 per cent of all mining ventures are unsuccessful, and his figures presumably refer largely to those properties in which evidence of mineralization has been considered good enough to warrant an attempt at commercial exploitation. It might be noted in passing that the figure of 1 out of 10 successful mining enterprises could be compared with 1 out of 9 successful wildcats in the oil industry, the current discovery ratio.

Discovery of new districts within the United States and of additional ore bodies in known districts will probably depend increasingly on techniques now being developed to discover blind ore bodies. These include geologic, geophysical, and geochemical methods.

There is far too strong a trend toward concentrating all efforts on the immediate practical objective of finding ore at low cost—a general feeling that research in economic geology means research in field techniques aimed at improving rule-of-thumb methods. However, if we learn more about the processes that control ore deposition we could apply that knowledge toward materially improving discovery rates.

May I point out that the recent amazing practical developments in nuclear physics are built upon innumerable man years of pure research by highly talented scientists with no thought of practical application of their work. The present opulence of the research physicist's laboratory layout, as well as the physicist's own much-increased income, stems from the discovery that his work is of direct, practical importance to the military, and ultimately perhaps to the private citizen. None the less, the current drive for practical results tends to impose a "brown-out" (President's Materials Policy Commission, 1952, p. 141) in the unpredictable field of pure research where, for the sake of learning more about some interesting little puzzle in the science, men may happily spend their lifetimes in obscurity. The field of economic geology has been pitifully neglected by research scientists through the years. We know little more now than we did 50 years ago about the chemical processes responsible for the deposition of ores, in contrast to the satisfying growth of knowledge in petrogenesis. We need more men in experimental geology who are eager to discover more about ore genesis, regardless of the practical applications of their discoveries; men whose motto might be the old proverb of Solomon: "It is the glory of God to hide a thing but the honor of a king is to search out a matter."

At the present time adequate funds to finance the basic research needed in the geology of mineral deposits are all but impossible to get from the mineral industry unless the question, "What's in it for us?" can be answered to the satisfaction of the mining company, and with their present outlook I doubt that this can be done. But eventually funds and personnel will be found for laboratory and field research—research that ultimately will yield methods that both cut down the target areas for physical exploration and minimize the number of blanks drawn by exploratory drill holes. Laboratory work on many fundamental problems lags for the moment, but we also need more good field geologists, explorer-minded, adventurous, sturdy, self-sufficient, scientific observers with a good background of chemistry, physics, and mathematics. The present and future sources of the mineral supplies that they must find are world-wide and emphasize the mutual dependency of the peoples of the world.

I am not going to say how soon the various mineral deposits currently supplying our industry will become depleted. It is sufficient to point out that all mineral deposits are ultimately exhaustible and that a continuing supply of minerals depends on discovery. It is clear that the depletion of known deposits poses a difficult problem if blind ore bodies must supply their place. As physical exploration is expensive and geologic work relatively cheap, it seems apparent that the lowest discovery costs will result from spending more money on geologic work and associated discovery techniques—and on the research to support them.

The tempo of exploration and development should be adjusted to our current and future needs for the various mineral raw materials and to our resources, and at present no adequate mineral-resource appraisal group exists either in the government or in the mining industry. This problem has been well covered in the monumental report of the President's Materials Policy Commission (1952a, p. 25–27, 169–171; 1952c), and I need only comment on it briefly: The mining industry still has learned little about the advantages of co-operation amongst competitors and stands in sharp contrast to the excellent example set by the highly competitive oil industry. As a result we know far too little of our country's mineral reserve position. The importance both to our security and to our economic future requires that a competent organization be set up soon, to make a continuing appraisal of the country's resources and its needs. Such a group would presumably collect and evaluate geologic and industrial data both from home and abroad, for use in anticipating future requirements. Economic, political, geographical, and geological factors must all be evaluated, and this is work for career specialists. A start in this direction was made by Lasky (1950; 1951) a few years ago, but unfortunately the work was discontinued.

The areas selected for mining geologists to explore may in future depend largely on statistical studies of ore-deposit populations to appraise the probability of ore occurrence in certain regions, developing and extending the contribution made by Nolan (1950) in his recent presidential address.

Such a study could well be one of the assignments of a Natural Resources Appraisal group and could lead to the recognition of potentially productive areas worthy of high priority in exploration.

Both Nolan (1950) and Lasky (1947) have struck an optimistic note in pointing out the possibility of ultimately finding districts or at least major ore bodies beneath the alluvial cover that blankets so much of the West. Large bodies of ore must indeed exist beneath such unconformities and doubtless also beneath many others—especially the great unconformity that separates Precambrian from younger rocks. It should be pointed out, however, that even if the existence and precise location of ore bodies under valley fill were known, many could not be mined economically because of heavy cover and the high costs of pumping from the water-logged alluvium of the intermontane valleys. For many years to come our search for blind ore deposits will be confined to areas where the cover is relatively thin. Even after eliminating the great expanse of economically unminable ground, however, there remain large areas concealed beneath unconformities where valuable ores may eventually be discovered.

The time lag between discovery and production, or in reopening a closed mine, is a factor of vital importance in considering either utilization of newly discovered deposits or the reserves in mines temporarily shut down. It is easy to be misled by apparently reassuring figures for the reserves of ore of the various metals. Reserve figures do not stress the economic factor that attends their exploitation. We may have reserves of lead or copper sufficient to last the nation at the expected demand rates for 20 years, but, if the national demand for these metals were supplied by cheaper foreign ores, we might soon be without domestic copper and lead mining industries. The interval between the discovery of a deposit and the time when it produces ore is usually measured in years, sometimes many years. Before the productive stage is reached, there is always the alarming possibility that new deposits will be discovered in areas where they can be marketed so cheaply that the one in which our money and time has been invested will be faced with an unprofitable market. A further hazard to large and relatively inflexible operations is the ever-present danger of profit confiscation through increased taxes or compulsory wage boosts, a threat that tends to discourage investment of venture capital in long-term enterprises in the United States as well as in many other countries.

Ideally, under free enterprise, any source of raw materials that cannot produce competitively with others should be a dead duck, but marginal producers within the United States have been exceedingly and successfully vocal in the environs of Congress. Under a really

free enterprise economy, one with international free trade, substantial amounts of domestic output would be cancelled out and replaced by cheap foreign sources of raw material. The ocean haul per ton mile costs only about 5 per cent of rail haul. But as a matter of national and economic security it is essential that we maintain a healthy mineral industry of our own for years to come, although subsidies must be granted in some form or other. A really free market departed our life with the first "protective tariff" long ago. Since then the question has been only that of the kind and amount of government subvention.

The problem of utilizing domestic ores has several facets: the problem of discovery itself must be solved satisfactorily; the time and cost factors must be estimated in the discovery, development, and productive life of a property; and to this end the market should be firm and dependable.

We know that the raw materials of the mineral industry are the basis of heavy industry, which in turn is the foundation for the rest of the manufacturing industry. They rise or diminish together, and it is vitally necessary both to our security and to our economic health that heavy industry in the United States maintain or exceed its current high level, and this means a continuing or increasing demand for raw materials. This does not necessarily mean a continuation or increase of the present high level of activity of the mineral industry *in the United States*, because ultimately much may be imported from abroad. But we *must* have minerals.

Truly competitive mineral prices are not really desired by even the most ruggedly individualistic mining men—unless their larger holdings are in foreign fields. Most domestic producers advocate tariff barriers to prevent competition of foreign ores, and their demands will grow more intense during a deflationary cycle such as may be expected when our industrial output again moves ahead of our markets, even though domestic sources are quite inadequate to supply the curtailed demand. Because of the relatively unfavorable current tax structure for corporate ventures in large-scale domestic mining, the uncertainty of prices, and the economic threat posed by highly paid and well-organized labor, it seems likely that much American venture capital will continue to move abroad for investment in mineral industries. This will accentuate the trend toward dependence on foreign sources and may force further the government control of industry and political redistribution of income from the higher income brackets. It also builds up a potential source of international trouble.

The movement of American capital into underdeveloped foreign areas parallels that of British capital during the late nineteenth century, after British mineral production had passed its peak and commenced the inevitable decline that goes with higher costs and lower-grade ores as depletion progresses. The exploitation of the underdeveloped areas and the fact that the flag often followed the successful prospector gave British imperialism its reputation.

A government is under great pressure to protect the "rights" of its citizens in foreign countries. Heavy investment in underdeveloped countries becomes a source of much friction when such countries decide to nationalize their domestic resources, a privilege supposedly inherent in a sovereign government. Our position with respect to such unhappy developments would be strong only if we already had substantial reserves of the mineral product in question either above ground or below, but within our own borders.

Nothing in the current scene indicates that the United States is regarded with such affection by foreign purveyors of raw materials as to lead to a "favored-nation" treatment in times of economic stress. On the contrary, we may expect cartelized prices as soon as economic conditions promise success for this favorite European economic weapon. With a short domestic supply, the threat of a squeeze-play price for raw materials abroad, and with labor difficulties at home, none but the hardiest entrepreneur would face the problems of industrial production with equanimity. Both private industry and the government therefore should bend every effort to assure a dependable supply of mineral products.

Concern for strategic raw materials—those

essential minerals in which we are notably deficient—has led the government to gradually accumulate substantial stock piles of many raw materials, held for emergencies when normal foreign sources are cut off. The stock piles are primarily a military precaution, and their size, grade, and location are not published (President's Materials Policy Commission, 1952a, p. 137–149).

In the see-saw of marine warfare, periods when our shipping is vulnerable to attack should be expected. In the second World War there was a six months' period when the German submarines destroyed most of our aluminum fleet, and seriously curtailed oil shipments from South America. Today the mineral industry is as obviously the Achilles heel of manufacturing as it was in 1942, and dependence on overseas shipments during war is to be avoided if possible. Before a stock pile can be considered adequate for war needs, one should know how long will be the war, and how long overseas freight will be disrupted. Neither question can be answered. The current trend of investing venture capital in mineral deposits abroad rather than at home may well prove shortsighted.

It seems clear that our domestic mining industry should be strengthened—not hamstrung; this means that the discovery rate should increase and that we must get more research on methods of mining and production. The assurance of a continuing strong domestic market would go far toward giving the mining industry an incentive to embark on the relatively inflexible large-scale, long-range enterprises that now characterize substantial production in nearly any segment of the mining industry.

The raw materials from farm, forest, and mine keep our economy going, and, the smoother their operation, the better the entire economy runs. When economic disaster overtook the farmer, the government accorded him price supports—to his immeasurable benefit and to the long-run benefit of the economy as a whole, especially that of the manufacturing segment. Mining men even more than farmers need the assurance of guaranteed minimum prices for their products and should be accorded a long-range price support program.

Security Through a National Materials Reserve

I suggest that we assure ourselves of satisfactory and dependable mineral supplies for industry, from both foreign and domestic sources, by steadily building up reserve stocks of all durable raw materials through the next twenty-five years, by means of a government-guaranteed floor price, but without ceiling prices, except in times of national emergency.

Our military stock piles should be kept intact. Separate from them, and entirely different from the buffer stocks discussed by the President's Materials Policy Commission (1952a, p. 88), I propose a large government-owned reserve of industrial raw materials as suitable to the economy of a great industrial power. Such reserves would constitute reservoirs of mineral wealth of far greater value and economic power than any gold treasure in Fort Knox or the Denver mint and would represent a perennial addition to national wealth. Incidentally, I see no compelling reason why we should not extend the idea of metal reserves as a basis for credits from gold and silver to all major industrial metals, but this is not the objective sought. The accumulation of such a government-owned reservoir of metal should be conducted so as to give the producer of mineral raw materials an assured market, similar to that enjoyed by the farmer today, but at a price guaranteed for a minimum of 3 years ahead, and reset once a year. Unlike perishable farm products, reserves of mineral raw materials do not rot when stored for many years, and storage should be inexpensive. If the price of metals continues to increase as the physical costs of extraction gradually, inexorably, rise, the greater value may through the years be enough to allow administration of this program without loss to the government. Eventually, say, after a 5-year reserve has been built up, metals bought years ago could be withdrawn as needed, but this would normally be a condition not achieved till the 1970s.

The building up of metal and mineral reserve stocks of the sort I suggest would, I believe, be one of the most potent factors for preserving peace and harmony amongst the family of nations that can be devised. It could

guarantee a stable fair market both for production at home and production abroad, and at the same time do away with the threat of cartelized and exorbitant prices which otherwise will continue to be a source of increasing friction between nations. It would assure a market that would give underdeveloped nations the dollars they so desperately need, as well as the dollar-poor industrial nations whose foreign markets would then be strengthened. It would do much to increase the standard of living in such areas and also within the United States. Ultimately it should become a bulwark of national security, and at the same time increase international amity and economic strength.

I would emphasize that the primary objective sought is the multi-metal reserve, not the price support. Of all the methods that can be devised for building up this reserve at a moderate rate, a rate that would help the mineral industry and not disrupt our industrial economy, the method that seems the least susceptible to political minority pressures and the one most easily administered would be that of the guaranteed-price-support plan. The prices could be adjusted to increase the reserves at a fairly regular rate, perhaps equivalent in amount to approximately 20 per cent of our industrial consumption per year.

The accumulation of treasure anywhere invites looting, either by internal or external plunderers. Undoubtedly political pressure would be brought to bear on the national government to release portions of the reserve for the benefit of the industrial jackals that occasionally provoke headlines on graft and corruption in government. The number of these is small, and a multi-metal reserve should be no more provocative than the many possibilities of a "quick buck" commonly believed to be associated with heavy Federal spending.

It is, of course, apparent that a price support would maintain higher prices during a general economic decline and would encourage the development of substitutes for the various metals. This in itself, I believe, would be a good thing for our economy in the long run, but might be opposed by major producers. A supported price would also cut the competitive price benefits to manufacturers slightly, but it is well known that the price of the raw materials is only a minor cost to the manufacturing industry, and fluctuations of 20 per cent in the cost of metals would not appreciably affect manufacturing costs, whereas it might make or ruin the mining industry. Perhaps the factor most feared by industry in setting up price supports (Not price ceilings!) is that of a bureaucratic administration which would ultimately set prices and control production, advancing us toward a government-managed economy. That this is a possibility anyone will admit. That it is a probability only the most fearful would agree.

Accumulation of a reserve at the rate of 20 per cent per annum would require more than 25 years to achieve the equivalent of a five-year consumption reserve, and, until such a reserve had been completed, price *support*, not price or production control, would be required. There is, perhaps, no good reason to set any arbitrary upper limit on the size of this reserve, just as no definite limit is set for the size of our gold reserves.

In conclusion, after considering the chief factors adverse to a multi-metal reserve, I return again to its manifold advantages. It would give a predictable basis for wage negotiation. It would give assurance of fair returns for long-range development programs in the mineral industry, and thus do much to take care of the time lag in the development of mines. During depression as well as in normal times it would help greatly in bringing venture capital back into the mineral industry by maintaining a healthy, stable mineral industry both here and abroad. It would also help minimize labor troubles and would preserve a skilled mine labor force. A guaranteed minimum price in the mineral industry would act as an industrial balance wheel during periods of depression, not like sand in the bearing box as have the uncontrolled price drops of the past. The guaranteed price for domestic ores should remove the pressures of both labor and management for high tariffs. The guaranteed price to foreign nations would give them dollars in exchange for their raw materials and thus would tend to hold up foreign economies much as the Marshall plan has done in the past, but with this great difference—we would be accumulating tangible assets of immeasurable value to us

in the future. In building up this reserve we would diminish rather than increase international tensions. The reserve should ultimately give us tremendous economic power, and its value in terms of security during a hot war cannot be overestimated. Finally this would be a price-support plan that could pay for itself in the course of time by virtue of the increase in value of the metal through the years. And although I have visualized this primarily as a reserve of metal, I would limit it only to those raw materials of industry that can be stored without deterioration, and which require a minimum of care. If we gave foreign nations the opportunity to sell metal and ore to this country so as to gain dollar balances we might even attain eventually the happy position of becoming a debtor nation and thus able to export some of the surplus that now plagues us, and do it on a sound economic basis!

References Cited

American Iron and Steel Institute: *Annual Statistical Reports*, Am. Iron and Steel Inst., New York.

American Iron and Steel Institute (1944) *Steel's war record*, Am. Iron and Steel Inst., New York.

Baruch, Bernard (1921) *American industries in the War*, War Industries Bd., Rept., p. 110.

Clarkson, G. B. (1923) *Industrial America in the World War*, Houghton-Mifflin Co., New York.

Hodgson, J. G. (1932) *Cancellation of international war debt*, H. S. Wilson Co., New York, p. 212.

Hook, C. R. (Armco Steel) (1951) [Interview], U. S. News and World Rept., June 8.

Keyserling Report (1952) *Economic Report to the President, January 1952*, Hearings before Joint Committee on the Economic Report, 82d Congress of U. S., Washington, D. C.

Lasky, S. G. (1947) *The search for concealed deposits, a reorientation of philosophy*, Am. Inst. Min. Metall. Eng., Tech. Pub. 2146; Discussion, Tech Pub. 2377, 1948.

— (1950) *How tonnage and grade relations help predict ore reserves*, Eng. Min. Jour., No. 4, vol. 151, p. 81–85.

— (1951) *Mineral industry futures can be predicted*, Eng. Min. Jour., No. 8, vol. 152, p. 60–64.

Mineral Industry (Annual Reviews 1892–1941), McGraw-Hill Book Co., New York.

Minerals Yearbook (Annual Reviews since 1934) U. S. Bur. Mines, Washington, D. C.

Mulhull's Dictionary of Statistics (1892), Rutledge and Sons, Ludgate Hill, England.

National Industrial Conference Board (1939) *Enterprise and social progress*, New York.

—— —— —— —— (1952) *Growth patterns in industry*, Studies in Business Economics, No. 32, New York.

Nolan, T. B. (1950) *The search for new mining districts*, Econ. Geol., vol. 45, p. 601–608.

Oldham Master Cotton Spinners Association of Lancashire, Lancashire, England.

President's Materials Policy Commission (1952a) *Resources for freedom, Vol. I, Foundations for growth and security*, Govt. Printing Office, Washington, D. C.

—— —— —— —— (1952b) *Resources for freedoms, Outlook for key commodities, Vol. II*, Govt. Printing Office, Washington, D. C.

—— —— —— —— (1952c) *Resources for freedoms, Selected reports to the Commission, Vol. V*, Govt. Printing Office, Washington, D. C.

Steel (Weekly magazine) Yearbook for 1952, Cleveland, Ohio.

U. S. Bureau of the Census (Annual reports since 1879) *Statistical abstracts of the United States*, Washington, D. C.

U. S. Bureau of the Census (1949) *Historical statistics of the United States, 1789–1945*, Washington, D. C., 363 p.

U. S. Department of Commerce (1951) *National income and product of the United States, 1929–1951*, Survey of Current Business, Supplement, p. 152.

War Production Board (1945) *Wartime production achievements 1945*, Washington, D. C.

Weintraub, Sidney (1951) *Income and employment analysis*, Pittman Pub. Corp., New York, p. 64.

Wheildon, L. B. (1947) *Notes on needs for basic steel*, Steel Capacity, Editorial Research Repts., vol. 2, p. 777.

White, J. A. (1951) *Review revision of 1951*, Hearings before the Committee of Ways and Means of the House of Representatives, 82d Congress, March 5 *et seq.*, pt. III, p. 1608.

Wright, C. D. (1894) *The slums of Baltimore, Chicago, New York, and Philadelphia*, U. S. Com. Labor, 7th Spec. Rept., Washington, D. C.

U. S. Geological Survey, Federal Center, Denver, Colo.

Manuscript Received by the Secretary of the Society, October 31, 1952.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 64, PP. 127-150, 15 FIGS. FEBRUARY 1953

EXAMINATION OF THE PHYSICS OF THEORIES OF OROGENESIS

By Adrian E. Scheidegger

Abstract

This paper investigates the problem of the physical causes of the present shape and structure of the earth's surface features. A physical process, called orogenesis, is defined as the cause of the surface features of our planet. The several theories of this process are reviewed and criticized from the standpoint of a physicist.

The properties of continuous matter which could give rise to orogenesis can be divided into yielding and flowing. Theories assuming yielding within the orogenetic shell thus form one large group, those assuming flowing form another. Before treating each group of theories, the physical background necessary for a consistent analysis is discussed.

Finally, an outline is given of how much credit the different theories receive in literature. Only two theories are at all widely accepted, and a decision between these two theories can hardly be expected upon physical grounds until more specific data are known about the interior of the earth.

CONTENTS

	Page
Acknowledgments	127
Introduction	128
Continuous matter	128
Theories of orogenesis based upon failure phenomena	130
Physical basis: Failure patterns in spherical shells	130
Geological implications	133
The contraction hypothesis	133
Theories assuming yielding	134
Theories assuming fracture	136
Theories of orogenesis based upon flow phenomena	138
Physical basis: Flow of matter and heat	138
Geological implications	142
General statement	142
Undation theory	142
Continental drift theory	143
Convection currents	143
Conclusion	148
References cited	149

ILLUSTRATIONS

Figure	Page
1. Macrocosmic plastic failure of a spherical shell as seen in meridional section	131
2. Slip lines in the form of logarithmic spirals with symmetrical stress state	131
3. Plastic slip lines underneath a cylindrical stamp	132
4. Stresses in the earth according to the contraction hypothesis	133
5. Distribution of the initial movements in a deep focus earthquake	135
6. Gravity anomalies and vertical distribution of the foci of deep earthquakes	136
7. Diagrammatic cross section across a double mountain arc, such as those of Western North America	137
8. Sliding fracture about a weak point on a cooling earth as the cause of an arc	138
9. A system of convection currents in the earth	140
10. Connection between the torque and the angular momentum in Reiner's rotation viscosimeter	141
11. Comparison of plastic and viscous lines of flow in a special case	142
12. Stereogram of a model experiment with a rotating drum in a viscous liquid	144
13. The two possible types of convection currents	146
14. Possible formation of continents and oceans by underlying convection currents	147
15. Map (on Mercator's projection) showing the hypothetical system of convection currents giving rise to the distribution of continents and oceans	148

Acknowledgments

It is a pleasure to thank Professor J. Tuzo Wilson, who suggested the scope of the present research, for his unceasing interest and valuable advice. The National Research Council of Canada sponsored the present work by grants to the Geophysics Laboratory of the Univer-

sity of Toronto where the writer carried out the present investigations during the summers of 1950 and 1951. The friendliness and excellent conditions for work provided by these institutions are gratefully acknowledged.

Introduction

The problem of the physical causes of the present shape and structure of the surface features of the earth has puzzled geologists and geophysicists for a long time. A great number of theories have been proposed to solve the problem, and new ones are still being advanced.

Some of these theories have been postulated merely to explain certain restricted features that were found by geological exploration without reference to or examination of the basic laws of matter that must underlie every physical theory. It therefore seems worth while to review and criticize the accumulated material and to try to do this from the neutral standpoint of a physicist.

The physical causes of the present shape and structure of the earth as exhibited by geological exploration are usually ascribed to a hypothetical process called orogenesis. Geologists and geophysicists are generally agreed that orogenesis must take place either in the crust or in the upper part of the mantle of the earth with the core playing only an indirect role as heat supplier or the like. Thus, it is natural to assume that orogenesis takes place in a rather thin layer, which may be termed the orogenetic shell of the earth.

Any theory of orogenesis, to be physically valid, must be based upon the mechanics of continuous matter. Unfortunately, very little is known about the mechanical behavior of those outer layers which might play the role of an orogenetic shell. Only for the outermost few kilometers do we have more or less definite data, and even there we do not know how the materials behave during prolonged time intervals. It is well known that the states of matter may change when temperature is altered, but also matter may behave quite differently when different time intervals are considered, or when other dynamical variables are changed. Thus, the orogenetic shell might have any mechanical properties ranging from those of a brittle shell to those of a layer of a liqui below the crust.

It is therefore necessary to review the be havior of continuous matter in general befor we consider spherical shells. One can divide th properties of continuous matter into yieldin and flowing. Theories assuming yielding within the orogenetic shell will thus form one larg group; those assuming flowing will form another. The physical background needed fo a consistent discussion is given before each group of theories.

In the final section, we shall try to outlin how much credit the different theories of oro genesis receive in the literature. Only two theories are at all widely accepted and a de cision between those two theories can hardly be expected upon physical grounds until more specific data about the interior of the earth are known.

Continuous Matter

The behavior of continuous matter has been studied extensively in the engineering literature, because of its importance in connection with strength of materials. Nadai (1931), Timoshenko (1942), and Freudenthal (1950) have reviewed the subject and given references to original articles. A theoretical treatment has been given by Reiner (1949); his approach has proved very useful in this investigation. The following paragraphs summarize the principal conclusions of the theory.

If one says that some particular substance is brittle, tough, or ductile, it must be realized that those expressions are idealizations. No real substance is ideally brittle, or tough, or ductile; it may behave in different ways under different circumstances. Thus, real matter behaves in a very complex way, which may be approximated to in theory by the device of a series of idealized substances. One is therefore led to consider a set of ideal substances with definite properties. The properties of any real substance will then be a "mixture" of those of two or more "component substances."

The following ideal substances are important.

THE HOOKE SOLID: This is a body that satisfies Hooke's Law: For a linear stress, strain is proportional to stress. In tensor representation,

this means that the isotropic and deviatoric components of the strain and stress tensors are proportional to each other. One needs therefore, two independent constants to characterize such a material. For these the bulk modulus κ and the shear modulus γ may be chosen. If both these constants are infinite, one obtains the special case of a perfectly rigid body. The theory of the Hooke solid is one of the classical pieces of applied mathematics and has been investigated extensively (*See* Love, 1927; Sokolnikoff, 1946). A good approximation of a Hooke solid is a piece of rubber, if it is not stressed too extensively.

THE NEWTONIAN LIQUID: The opposite extreme to the Hooke solid is the Newtonian liquid. In this case the stresses are related to the time derivatives of the strains in the same way as they are related to the strains themselves in the case of the Hooke solid. Two independent constants are used to describe such a material; those generally chosen are the bulk viscosity η_v and the shear viscosity η_s, but the bulk viscosity is usually neglected. If both these constants are zero, one obtains an inviscous fluid (*See* Lamb, 1932; Goldstein, 1938). A good approximation to a Newtonian liquid is honey.

THE ST. VENANT BODY: Most real bodies which approximate to a Hooke solid for small stresses, start to yield when a certain stress ϑ is reached. After this "yield" stress is reached, the material starts to flow, but it does not flow like the aforementioned liquids. Its flow resembles what might be called "plastic" flow rather than "liquid" flow. Under the same stress the material is continuously deformed. A new "ideal" body has therefore been suggested, the St. Venant body.

The stress at every point of a body is mathematically represented as a tensor. One has therefore to state the exact condition for which the stress tensor at a certain point of the body becomes a yield stress tensor. Mises has expressed such a condition by taking certain invariants of the latter; Hencky arrived at the same condition by a different approach. This yield condition is therefore called the Mises-Hencky condition. (For the detailed mathematical formulation of this condition, *see* one of the textbooks on plasticity, e.g. Nadai, 1931.)

The physical bases of the "theory of plasticity" as so stated have been questioned on several occasions, as for instance by Stüssi (1950). Thus, several rival yield conditions have been postulated (*see* Prager, 1948b). Because of this uncertainty about the yield condition and the relative newness of the whole subject of plastic flow, very little has yet been done towards finding methods for solving the fundamental equations. Nadai (1931) lists some methods, and Prager (1948a) has given a graphical method, but the discovery of several variational principles (Sadowski, 1943; Prager, 1946; Oldroyd, 1947a) will likely be more useful in a final theory of plasticity yet to be developed. An extensive mathematical treatment of the subject has been given by Hill (1950).

Phenomenologically, one can state the following facts about the St. Venant body: The density of the material is the same at constant temperature. The direction of the principal strains and principal stresses always coincide. Within a material in a state of plastic flow, the material undergoes larger deformation along certain lines than in other regions. The lines are known as Lüder's lines or slip lines and have been found to be approximately the 45° isogonals to the trajectories of the principal stresses. The branch points of the slip lines give the natural border points between the "flowing" and the "solid" regions of the body. The slip lines form tiny furrows on the surface of the material, which is why they can be photographed.

A good realization of a St. Venant body is whipped cream; in that particular case the yield stress is very small.

COMPOSITE IDEALIZED BODIES: The linear superposition of the aforementioned three fundamental linear bodies leads to the general linear body. Several superpositions where only some of the possible components are present are also important.

A Hooke solid which exhibits at the same time the properties of a viscous Newtonian liquid is called a ***Kelvin body***. Such a body possesses both elasticity and viscosity. Thus the equation of state for a Kelvin body contains linearly the stresses, the strains, and the time

derivatives of the strains. It shows the characteristic property of an elastic after-effect. This means that, if a load is applied, the strains reach the values corresponding to those of a Hooke solid only after a certain length of time.

The Hooke body and the Newtonian liquid may be combined in a different linear way to obtain a body called a Maxwell liquid. The Maxwell liquid possesses elasticity and viscosity, but the equation of state contains linearly the stresses and the time derivatives of the stresses and strains. It shows, therefore, the characteristic property of creep. Under rapid changes of the stress, the material behaves like an elastic solid; given time, it "creeps" like a very viscous liquid.

A material which combines the properties of plasticity with those of a Kelvin solid is called a *Bingham body*. Its equation of state contains therefore a yield stress, the stresses, the strains, and the time derivatives of the strains.

We may conveniently say that the *general linear body* is described by the assumption of a Kelvin component and a Maxwell component with the St. Venant yield stress dividing flow from deformation. The materials in which the yield stress vanishes constitute the class of liquids; the rest are solids.

For solids and quasi-solids such as the Maxwell liquid, we must introduce a further concept: The breaking stress. In addition to yielding, such substances show the feature of rupture. It must be assumed that the molecular structure breaks down if the local stress tensor at a certain point becomes a breaking stress tensor. Again, one has to state a definite condition for which a stress tensor becomes a breaking stress tensor. This may be accomplished mathematically by stating conditions for certain invariants of the stresses. Now, if during a given deformation the breaking stress is reached before the yield point, we say the body behaves as brittle. When yielding precedes breaking, we call the behavior "plastic".

The theory of materials outlined so far is linear. It may be necessary to assume that the "constants" are actually not constants but functions of the stresses, etc. Bodies so characterized are non-linear bodies. For our investigation, however, the linear theory is a sufficient approximation.

A further remark concerns the phenomenon of failure. Failure has been introduced as either yielding or rupture and is thus a static concept. In many instances this is not a sufficiently close approximation to nature. Reiner, Freudenthal and Weissenberg (for the original references *see* Reiner, 1949) have therefore developed a dynamic theory of strength. The results of that theory for the constituents of a general linear body, are as follows: A Kelvin solid fails when the strain reaches a definite limit. The stress at which the material fails increases with the velocity of strain. A Maxwell liquid fails when the stress reaches a definite limit. The rate of strain at which the material fails increases with the rate at which the stress is applied.

The theories outlined here are purely phenomenological. Many attempts have been made to explain the behavior of continuous matter by microscopic models (*see* Freudenthal, 1950). In geological applications, however, the phenomenological approach is sufficient.

Theories of Orogenesis Based upon Failure Phenomena

Physical Basis: Failure Patterns in Spherical Shells

One group of theories of orogenesis depends upon the assumption that mountain building is an expression of failure of the outer portion of the earth. We shall therefore investigate the patterns which might occur in spherical shells because of failure of the material and see whether this suggests any manner in which the orogenetic shell of the earth may have behaved.

BUCKLING: Every linear body is considered to behave like a Hooke solid before the yield or breaking stress is reached. A Hooke solid cannot "fail" in the ordinary sense, but a phenomenon similar to "failure" can occur if, instead of one well determined state of equilibrium under a given load, an infinity of deformed states exist: the material is then said to buckle (*see* Timoshenko, 1936). The buckling of a shell can take place if the shell is under a pressure or similar force from the convex side, but not if it is under pressure from the concave side.

The elastic deformation of a spherical shell under different external conditions was first dealt with by Zoelly (1915). An improved treat-

ment of the buckling of a spherical shell under homogeneous pressure was given by Schwerin (1922). Recently, Leutert (1948) has solved the problem of the elastic deformation of a spherical shell under arbitrary external forces.

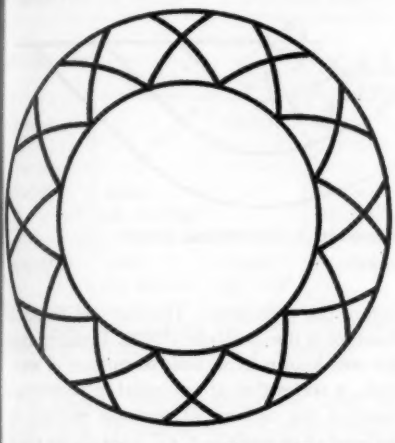


FIGURE 1.—MACROCOSMIC PLASTIC FAILURE OF A SPERICAL SHELL AS SEEN IN MERIDIONAL SECTION

These investigations show that the deformation of a buckling sphere is symmetrical about a diameter and that the deviations of the shape are given by a series of spherical harmonics along parallels of latitude associated with the diameter of symmetry. This theoretical result has been checked by various experimental tests.

YIELDING: As previously stated, yielding occurs in plastic solids as well as in Maxwellian liquids.

Considering first bodies of the St. Venant type, Nadai (1924) has indicated how to obtain the equations for the plastic flow of a spherical shell. The general case is very difficult to treat, and the only case yet solved which refers to our problem is that of the plastic deformation of a spherical shell under a pressure acting from inside. There, the trajectories of principal tension are the radii and meridians, so that the slip lines, being the 45°-isogonals to that system, have the form shown in Figure 1. No slip lines can appear on the outer surface of the shell, because at every point every direction is equally significant.

For the plastic failure of spherical shells in a limited region, no solutions are yet available. The case of special interest with respect to possible geological applications is that in which on a sphere there is a "weak point" (of symmetry) or a weak region, in whose neighborhood plastic yielding may occur. This is an idealization similar to assuming axial symmetry around a diameter of a sphere.

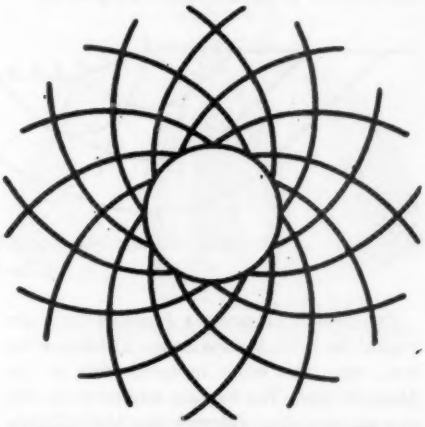


FIGURE 2.—SLIP LINES IN THE FORM OF LOGARITHMIC SPIRALS WITH SYMMETRICAL STRESS STATE A circle forms the boundary between the "solid" and "plastic" regions. (After Nadai).

The full solution of this case has not yet been achieved, but an approximate idea of what must happen may be gained by replacing the curved spherical shell by a plane with a two-dimensional stress state. For this special case, the equations of plastic flow have been solved. The result is that the slip lines are logarithmic spirals and the line joining all the branch points is a circle (Fig. 2; Nadai, 1924). A circle will be the natural borderline between the "plastic" and the "solid" regions on the surface of the material. This kind of failure has been tested by pressing a cylindrical stamp into steel.

The above simplification of the problem gives an idea of what happens only on the surface of an impressed shell. We want also to know what happens underneath the stamp. If the shell is thick, it can be approximated by a semi-infinite plastic mass into which a stamp is impressed, and the slip lines are as shown in Figure 3 (Hencky, 1923).

Nadai's (Fig. 2) and Hencky's (Fig. 3) results combined suggest that, in the case of a

spherical shell under tension (or compression) with a "weak region," the slip of the material occurs along surfaces whose traces on the shell are two families of logarithmic spirals with dip as shown in Figure 3. However, the problem is not believed to have been solved precisely.

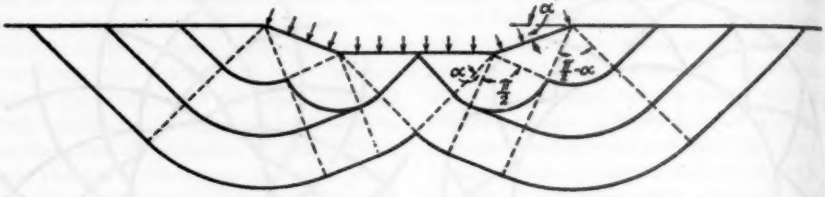


FIGURE 3.—PLASTIC SLIP LINES UNDERNEATH A CYLINDRICAL STAMP
(After Hencky)

The yielding phenomena discussed above are typical for a St. Venant body. Yielding, however, may also occur in quasi-solids of the Maxwell type. The loading conditions in this case are somewhat different: any load will produce yield (or creep, as it is now called), if applied for a sufficient time. The creep patterns seem very similar to the plastic flow patterns, although the creep conditions differ from the plastic flow conditions.

Macrocosmically, therefore, it is again true that, at any point on the surface of a shell creeping under a homogeneous strain state, every direction is equally significant. Thus slip or sliding lines cannot appear in this case.

As before consider the case, therefore, where there is a weak point (of symmetry) on the shell and where there are creep phenomena. This problem is not completely solved. For a qualitative investigation, however, we may replace a small portion of the shell by a disk. The creep of a disk under a symmetric stress state has been studied because of its relation to the important engineering problem of creep in rotating wheels. A rotating disk is only stressed by a tangential and radial tension; this is just the stress state which may be expected to occur in a shell with a "weak point" under internal tension.

Soderberg (1938), for the problem of creep in a rotating disk, found that the effect in the disk is only a slight generalization of what was found for plastic yielding. The slip lines will have a rough similarity to spirals. Although they are not as before logarithmic spirals, there will be two systems of such lines crossing each other and making equal angles with the radial direction.

FRACTURE: Failure of the material by actual fracture occurs if the breaking stress is reached before the yield point. The classical theory of fracture is due to Mohr (1928). Deduced from his well known hypothesis of rupture of materials, it states that at any point in an isotropic medium the surfaces of probable rupture are inclined at an angle $\phi \leq 45°$ towards the smallest principal stress (i.e. the greatest pressure). This implies that the intermediate principal stress has no influence on the fracture of materials.

In the case of a pure tensile test (degenerated stress state) the above statements do not determine the surface of rupture. Thus, one has to add that in this case the surfaces of probable rupture are perpendicular to the tensile stress.

Applying Mohr's theory to spherical shells, we note that tensile rupture may occur in a hollow sphere under a pressure from inside. This would lead to vertical cracks of irregular strike. If the pressure acts the opposite way, the hollow sphere would buckle elastically before it could rupture.

When the general case (not degenerated) of fracture of a spherical shell is considered, a "weak point" may again be assumed and the possible rupture patterns investigated in its neighborhood. If the "weak point" is a point of symmetry, a straightforward application of Mohr's theory shows readily that the patterns shown in Table 1 are possible.

A symmetric stress state as discussed here can occur in a sphere with a weak region and under additional thermal forces. More complicated stress states would produce more com-

plicated fracture patterns. However, such arbitrary stress states amount to introducing an *ad hoc* hypothesis and never can provide a real explanation of observed fracture patterns.

TABLE 1.—FRACTURES EXPECTABLE IN A SYMMETRIC STRESS STATE OF A SPHERICAL SHELL

Smallest stress	Intermediate stress		
	Vertical	Radial*	Tangential*
Vertical	—	straight dip <45°	circular dip <45°
Radial	spiral dip vertical	—	circular dip >45°
Tangential	spiral dip vertical	straight dip >45°	—

*"Radial" and "Tangential" are to be understood with respect to the point of symmetry.

The theories outlined above are valid for linear bodies. Mohr's theory of fracture is something of an oversimplification of the observed facts. In certain cases, more complicated patterns may occur, especially if fracture and yielding occur together. In this case the materials are said to be ductile. However, theories for such ductile materials are very incomplete. The only thing more or less certain is that fractures are very irregular and do not seem to fit into simpler schemes.

In discussing geological applications, we shall, therefore, use only those theories which are reasonably complete.

Geological Implications

The contraction hypothesis.—The theories of orogenesis which ascribe the shape of the earth to yielding phenomena of spherical shells as distinct from flow phenomena are based upon the so-called "contraction hypothesis", considered since the time of Descartes at least. (For reviews of some work bearing upon that theory, *see* Gutenberg, 1930; 1939, p. 188–193.)

A most important exposition of the contraction hypothesis was given by Jeffreys (1929). The earth is assumed to have been a hot, liquid body at one stage in its life. It solidified quickly and continued to cool by radiation. Jeffreys' theory is that the silicate mantle solidified from its base at the top of the liquid iron core outwards and has since been cooling by conduction without convection currents. From the center of the earth to within about 700 kms of the surface, there has not been time since the earth solidified for any appreciable cooling nor change in volume. Within the region from about 700 to about 100 kms, cooling by conduction is taking place and hence this shell or layer is contracting and being stretched about the unchanging interior. Hence it is in a state of internal tension.

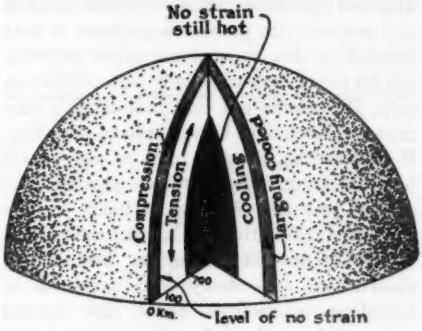


FIGURE 4.—STRESSES IN THE EARTH ACCORDING TO THE CONTRACTION HYPOTHESIS

Near the surface the rocks have already largely cooled so that at the surface they are in thermal equilibrium with the heat of solar radiation. They are therefore not changing in temperature and the cooling and contraction of the layer beneath them puts the outermost shell into a state of internal compression above a level of no strain at about 100 kms depth. This outermost layer is thus being folded up upon the shrinking interior. (*See* Figure 4.)

The power freed by the contracting layer is considered the cause of orogenesis.

It has been questioned whether the cooling of the earth would supply enough power to explain the orogenetic patterns. The presence of radioactivity in rocks provides a serious drawback to this theory because the heat generated by the radioactive elements in the surface rocks is so large as to allow question of the very assumption that the earth is cooling. However, recent determinations at Toronto of the radioactivity of many Archean type of

rocks suggest that the average radioactivity of the continental rocks has been exaggerated.

In this connection, Slichter (1941) investigated the problem of the cooling of the earth very carefully. He reviewed the observational data and hypotheses pertinent to that problem and indicated the possible importance of heat transfer by slow thermal convection currents, but his paper deals essentially with conduction only. He pointed out that radioactivity may cause the earth to be heating instead of cooling. If it is cooling, the rate must be very small, but, if heating, higher rates are possible. The surface heat flow fixes upper limits for the amount of radioactivity which may exist within 100 or 200 kms of the surface. But thermal observations and theory seem incapable of furnishing information about the thermal status of the earth at depths greater than 200 or 300 kms. Little correlation would exist between the distribution of radioactivity at depth and observed surface heat flux. Thus, the earth may be heating everywhere, cooling everywhere, or heating at some depths and cooling at others. In view of this state of complete uncertainty, Jeffreys' contraction hypothesis must still be accepted as a definite possibility in spite of attacks upon it. We shall, therefore, review the attempts to explain the more specific orogenetic features on the basis of the contraction hypothesis.

Theories assuming yielding.—Lake (1931a; 1931b) investigated the island and mountain arcs of Asia and postulated that those arcs were circular and that their poles or centers lay upon one or other of two great circles. He explained this particular geometrical configuration by supposing that each circular arc was the surface expression of a large thrust plane upon which movement was at right angles to the plane of the corresponding great circle. Thus he suggested that the Asiatic continent was being underthrust by the floor of the ocean from two sides along a series of large thrust planes whose outcrop was marked by circular offshore island arcs in the east and by circular mountain arcs to the south.

Lake's observations were confined to seven Asiatic arcs, but Wilson (1949) subsequently pointed out that the centers of all the island and mountain arcs active at the present time lie fairly well upon the continuations of the same two great circles, forming the two great belts of young mountains and arcs about the Pacific Ocean and from the Alpine region across continental Asia to Oceania and New Zealand. If this is true, the shrinking of the earth is occurring by failure along two great circles, but the fracturing is such that the actual edges always have the form of small circles with their centers near one of the great circles.

There are several difficulties to be overcome before this theory can be accepted. First, the mountain and island arcs are all more or less irregular and differ in size. Some are far from being circular and some show an increase in radius of curvature towards one end. Several have approximately straight extensions like Kamchatka or Sakhalin. The positions of the centers are thus somewhat arbitrary and hence the conclusion that the centers lie on two great circles loses some of its significance.

Second, deep focus earthquakes are often connected with the arcs. This seems to indicate that the mechanism of orogenesis is not connected with the outermost layers of the earth alone. If that is the case, the mechanism proposed by Lake needs modification to explain why the deep earthquakes lie upon surfaces that dip much more steeply than the thrust planes postulated by him on physiographic grounds.

Third, the question as to whether the type of failure propósed by Lake is compatible with the physical laws of failure of materials requires consideration. In Lake's theory the problem of the macrocosmic failure of the earth is essentially the same as the buckling of a spherical shell under a pressure acting from outside. We have already shown that the deformation of a buckling sphere is symmetrical about a diameter. Thus, the conclusion is that the mechanics of failure of a rigid elastic shell collapsing upon a contracting core as envisaged by Lake cannot account for the real shape of the arcuate failures upon the surface of the earth. Similar conclusions are reached when other types of macrocosmic failure of a spherical shell instead of buckling are considered.

It seems, therefore, that the only way to account for the actual shape of the arcs is to consider the failure of smaller portions than the

whole earth, and to consider that these portions are not homogenous.

Coulomb (1943; 1945) investigated the possible cause for the peculiar phenomena connected with the cross section of the arcs, especially for the fact that the foci of deep earthquakes connected with the arcs appeared to lie all on one straight line in any section. He explained such a line by assuming an orogenetic slip phenomenon occurring beneath the level of no strain (Fig. 5). The experimental determination of the motion in the hypocenter of a deep focus earthquake by Koning (1942) seems to support the assumption of such a slip phenomenon, but does not rule out the possibility that the motion of earthquakes be orthogonal to the focal surface instead. That would contradict Coulomb's idea of a slip surface, but it is considered a less likely mechanism for producing earthquakes than actual slipping along the surface.

However, provided that the motion is actually as assumed in Figure 5, Coulomb was able to explain not only the existence of a focal plane, but simultaneously the gravity anomalies around orogenetic belts. In the magma beneath the level of no strain, a constriction furrow is formed where the crust descends by the combined effects of gravitation and of the horizontal surface compression due to the contraction below (Fig. 6).

Coulomb leaves the question undecided which type of yielding gives rise to those phenomena. Plastic yielding as well as sliding fracture would seem able to produce the required pattern.

Wilson (1950, p. 155), investigating independently, came to similar conclusions as to the orogenetic cause of the mountain and island arcs, but he worked out the mechanism in much greater detail (Fig. 7).

The investigations mentioned so far deal only with the cross sections of island arcs. For a consistent theory, the arcuate surface structure of the orogenetic belts must also be explained. Scheidegger and Wilson (1950) found that possible bases for such an explanation would be furnished either by assuming plastic yielding or yielding by creep, or else by assuming sliding fracture.

According to the first assumption, an explanation of the shape of failure on the earth would be that around a "weak point" (of symmetry) where there is a branch point line (a circle with a small diameter), spiral-shaped slip lines form. Underneath each of those lines would be a surface dipping down into the earth.

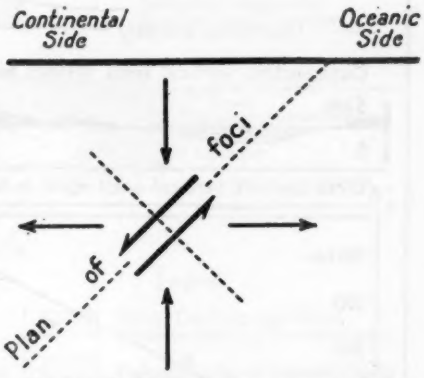


FIGURE 5.—DISTRIBUTION OF THE INITIAL MOVEMENTS IN A DEEP FOCUS EARTHQUAKE (After Coulomb)

If the margins of continents are assumed to be weak zones corresponding to branch point lines, then island arcs and perhaps marginal ranges might correspond to spiral slip lines springing from the margin of continents. The fact that the material along the slip lines undergoes a different kind of deformation from that in other regions might account for earthquakes and volcanoes near island arcs. Furthermore, the "skin" of the earth might be expected to be in process of folding because it has been becoming too large for the collapsing interior (*See* Geszti, 1929).

From the theoretical standpoint, there are some objections to this theory. Slip lines form a double family of curves crossing each other, not just single lines, and there is no evidence on the earth of two sets of arcs crossing one another at approximately right angles. Furthermore, each family of slip lines theoretically forms a great number of curves that cover a whole region quite densely. On the earth, there are only single spirals at comparatively wide intervals. There is no evidence that several arcs start from one region of weakness.

It might be possible to adjust the facts better

to the theory by geological explanations, such as assumption of a certain anisotropy in the earth, or by analogy with the well known feature in rocks that frequently only a single

Theories assuming fracture.—Accordingly, instead of assuming plastic yielding or yielding by creep as an explanation for island arcs, we shall assume fracture. An application of the

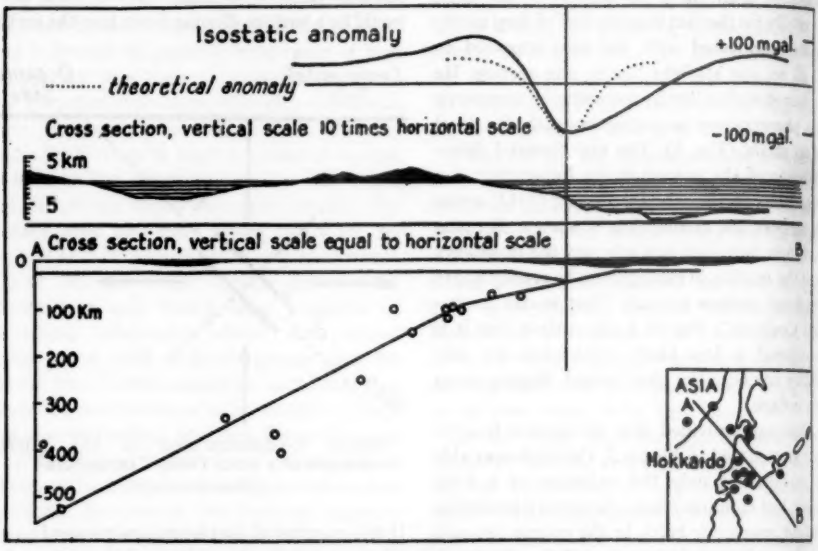


FIGURE 6.—GRAVITY ANOMALIES AND VERTICAL DISTRIBUTION OF THE FOCI OF DEEP EARTHQUAKES

(After Coulomb)

fault is evident although in theory there should be one or two whole families of faults. However, it will require further geological and geophysical explanation and evidence to justify fully the postulation of a plastic slip phenomenon as explanation for spiral-shaped island arcs and mountain ranges. Also the belts of failure would have to be spiral rather than circular. The same arguments apply to any explanation that arcs are due to yielding by creep.

Ruud (1938) also assumes plastic failure as the cause of primary orogenesis, but postulates that the arcuate structures upon our planet correspond to the branch point lines instead of the slip lines. Assuming circular symmetry, the primary orogenetic structures to be expected are ring-shaped craters like those on the moon. The theory was originally developed to explain those craters on the moon and then it was also applied to the earth. In this instance, a major difficulty seems to be that the chains of island arcs on the earth bear but little resemblance to the craters on the moon.

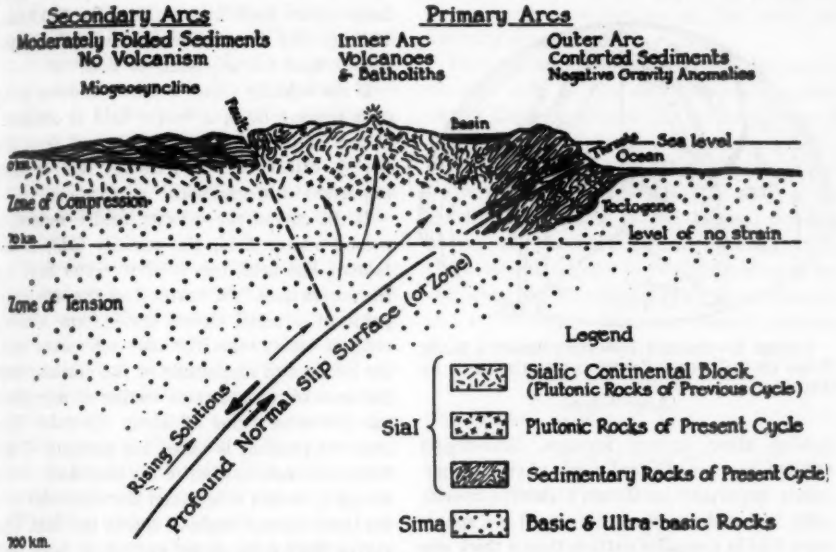
ideas of Mohr's theory to geological questions has already been given by Seigel (1950) whose results agree with the following statements.

If circular symmetry is again assumed around a point (or a weak region), the greatest pressure in the asthenosphere must be assumed to be vertical (or nearly so) because of the weight of the overlying material, and because below the level of no strain the other principal stresses are tensions, that is to say less than standard pressure. The theory (Mohr, 1928; Seigel, 1950) then predicts that the failing surfaces will be inclined at less than 45° to the radial direction of the sphere and parallel to the intermediate principal stress. This can be either the tangential direction to a circle around the point of symmetry or the meridional direction.

The first of these cases might explain circular island arcs and mountain ranges for it leads to conical fracture with a dip of about 45°.

On the other hand, if island arcs are considered to be spiral-shaped, the theory would have to be modified. One might assume, for instance,

that the stress state is symmetrical with respect to a point in a certain limited region only, and that farther away there is an undisturbed stress distribution. Thus, starting in a "weak region", approximately circular, this theory yields a tenable explanation of the actual shape of the island arcs. Benioff (1949) has shown the dip of the zone which contains the earthquake foci



Diagramatic Cross Section of Double Mountain Range

Great exaggeration of vertical scale in upper part

FIGURE 7.—DIAGRAMMATIC CROSS SECTION ACROSS A DOUBLE MOUNTAIN ARC, SUCH AS THOSE OF WESTERN NORTH AMERICA

(After Wilson)

a sliding crack could develop in a circular manner before finally flattening out into a tail of irregular strike. Such a pattern is actually observed in the archipelago of the Marianas.

Of course, a suitable stress distribution could also produce spiral-shaped sliding fracture. In such a stress state, however, the intermediate and smallest principal stress could no longer be tangential and meridional with respect to a point of symmetry. This would give rise to a much more complicated stress distribution, from a mathematical standpoint, than those considered heretofore. In the present case, the stress-distribution would itself have to be spiral-shaped. It would, therefore, as an *ad hoc* hypothesis provide no real explanation for the shape of the island arcs for there immediately arises the question as to why the stress state should be spiral-shaped.

Nevertheless if the arcs are considered to be to be about 45°. Furthermore, actual sliding fractures seem more likely to cause earthquakes and to be connected with ocean deeps and volcanoes than the macroscopic analogue of Lüder's lines. Deviations from circular shape of the arcs would have to be explained by geological irregularity. The surface features would again be due to an adjustment of the crust to the shrinking interior according to the ideas of Geszti (1929). Therefore sliding fracture seems the most likely cause for the form of the orogenetic belts, provided one wants to maintain the contraction hypothesis (*see* Fig. 8).

On these grounds Wilson (1951) has applied this physical process to obtain a coherent theory of the growth of terrestrial features. He shows that the geology, the volcanism, the distribution of earthquakes, and the whole pattern of existing active mountain ranges may be

explained in terms of this process. He concludes that this mechanism is physically valid and would serve to explain the growth during geological time of continents, oceans, and atmosphere on a planet initially uniform and

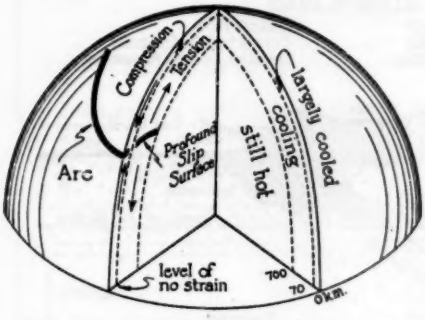


FIGURE 8.—SLIDING FRACTURE ABOUT A WEAK POINT ON A COOLING EARTH AS THE CAUSE OF AN ARC

(After Wilson)

lacking these surface features. Scheidegger (1952b) has investigated some physical arguments important in Wilson's theory. Specifically, he has shown that a thin crust of a sphere must fold in a smaller pattern than a thick one if the core shrinks by the same amount; that the speed of cooling of a sphere decreases if some radioactive and hence heat-generating material is moved from the surface towards the center (and conversely); and that at the level of no strain of a cooling sphere the temperature-depth curve must be almost straight.

It is of some interest that most of the foregoing discussions remain valid if, instead of a contracting earth, an expanding earth is substituted. Most of the theory of continuous matter is independent of the *sign* of the stresses so that similar failure patterns are produced in both cases. If a strongly radioactive earth is heating up, similar physical principles would underlie its surface patterns. The fissures, earthquakes, etc. again could occur in arcuate belts; but it would be rather difficult to account for the fact that mountains are being folded.

THEORIES OF OROGENESIS BASED UPON FLOW PHENOMENA

Physical Basis: Flow of Matter and Heat

Another group of theories of orogenesis ascribes the patterns on the surface of the earth to flow phenomena in the orogenetic shell: the theories of undation, of continental drift, and of convection currents.

FLUID KINEMATICS: In this connection, it seems useful to review first some of the basic facts about fluid kinematics. (*See* Goldstein, 1938, p. 26.) The theorems ensuing from that theory hold for any kind of flow.

If the velocity vector is drawn at every point of a moving fluid, a vector field is obtained. If this vector field is independent of time, the flow is called "steady". Steady flow is most important for geological applications.

If the curl of the velocity field is formed, a second vector field, the *vorticity* field, is obtained. The field lines of that vector field are the vortex lines. The vortex lines through every point of a small closed curve form a tube, called a vortex tube. For any such vortex tube, the product of magnitude of the vorticity and the area of normal cross section at any point has the same value all along the tube. This constant product is called the strength of the tube. As a consequence of the constancy of the strength, vortex tubes (and therefore also vortex lines) cannot begin or end in the fluid. The vortex lines form closed curves, or begin and end on the boundaries of the fluid, or, if we suppose the fluid to be unbounded, they go to infinity.

Circulation is associated with a closed circuit drawn in the fluid. Mathematically, the circulation round such a circuit is defined by the integral $\oint v_s ds$ taken once completely round the circuit, where v_s is the component of the fluid velocity in the direction of the tangent at the element ds of the circuit. This circulation may be shown to be equal to the total strength of all the vortex tubes that thread through the circuit, and the difference of the circulations in any two circuits is equal to the total strength of all the vortex tubes that pass between them.

The definitions of vorticity, vortex lines, vortex tubes, and circulation, together with the theorems concerning the strength of a vortex tube and the connection of circulation therewith, are purely kinematic or geometrical matters, completely independent of the presence or absence of stress. They hold, therefore, for *any* kind of flow.

INVISCOUS FLOW: Surveying the properties of

flow which will have a bearing upon geology, let us start with inviscous liquids. Of special interest is the case where a liquid layer upon a sphere (in the gravitational field of the latter) is oscillating. Van Bemmelen and Berlage (1935) have investigated this problem mathematically and found that the oscillations appear to be aperiodic for very short and very long waves, but may be periodic for medium wave lengths. A tendency to isostatic equilibrium seems to produce aperiodic oscillations only; a tendency to hydrostatic equilibrium appears required to produce periodic oscillations. This will be important in connection with the undation theory.

Of similar interest is the case of a rotating liquid sphere with masses floating upon it. It has to be expected that the rotating mass of liquid will hold together due to gravitation and assume the form of a geoid. Eötvös (1910) calculated that any floating masses upon such a rotating geoid will tend to drift towards the equator. A newer discussion of that result was given by Ertel (1931; 1935). This is important in connection with the continental drift theory.

Other theories of orogenesis postulate thermal convection currents in the interior of the earth, assuming there a more complicated material than an inviscous liquid. Therefore, the important problem is that of the free thermal convection currents in various materials between two concentric spherical shells of different temperatures, subject to a gravitational field originating in the center. Unfortunately, we cannot simply study the patterns of currents and later add the thermal facts, as was done for theories based on failure. The failure was independent of the manner in which the stresses and strains were produced, but the pattern of currents is *not* independent of the mechanism maintaining them.

The problem then is: to study possible convection currents in various materials that can occur because of temperature differences. Such currents, naturally, can only occur in continuous matter capable of flow, that is, both in the types of liquids mentioned under "continuous matter", and also in certain types of solids, if the stresses due to temperature differences are large enough to overcome the St. Venant yield stress.

VISCOUS FLOW: Heat transfer by liquids of the Newtonian type has been investigated because of the importance of heat transmission in engineering problems. Some results are thus available in textbooks (e.g. McAdams, 1942). Those results have been obtained with particular reference to water and air, for which the viscosity is very small.

Dimensional analysis shows that the motion depends only on two dimensionless numbers: on the Reynolds number and on the product of the Grashoff and the Prandtl numbers. Let c denote the specific heat per unit mass of the material, D a characteristic diameter, g the gravity acceleration, k the thermal conductivity, ΔT the temperature difference, V a characteristic velocity of the fluid motion, β the coefficient of expansion (per °C), η the viscosity and ρ the density, then the Reynolds number R is given by the equation

$$R = DV\rho/\eta$$

the Grashoff number G by

$$G = D^3\rho^2 g\beta\Delta T/\eta^2$$

and the Prandtl number P by

$$P = c\eta/k$$

If the Reynolds number is small, the motion is laminar or steady; above a certain limit it becomes turbulent.

For laminar motion, the product λ of Grashoff and Prandtl numbers governs the thermal convection. Jeffreys (1926; 1928) has deduced theoretically that no stable thermal convection should occur unless λ is at least 1709. In his papers, the direction of the thermal gradient is supposed to coincide with the direction of the gravity acceleration. The formulas were developed in connection with the study of thermal convection in air or water between two horizontal plates at a given temperature difference. The convective motion between two plates is pictured as occurring in the form of convection cells. A convection cell contains a vortex tube which is closed within the cell. The picture is thus in agreement with the kinematical properties of vorticity.

This theory has been tested experimentally. Schmidt and others (1935; 1938) have employed an optical method to study the mechanism of heat transfer by natural convection above a horizontal plate. The photographs do indeed

show a cell-like pattern under certain conditions. When the product of Grashoff and Prandtl numbers is above 2000, alternate

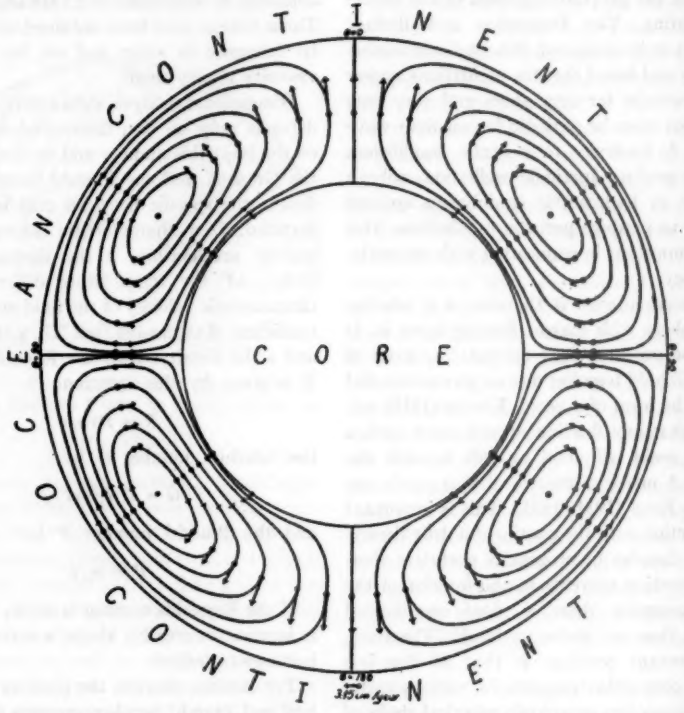


FIGURE 9.—A SYSTEM OF CONVECTION CURRENTS IN THE EARTH
(After Pekeris)

portions of the fluid circulate upward and downward in streams of substantial width. As the characteristic product increases, the rate of fluid circulation increases, until finally turbulence ensues at $\lambda = 45000$.

Jeffreys' results have been reviewed and extended by Low (1929). Pellew and Southwell (1940) extended the results of Jeffreys and Low, and made investigations under different sets of boundary conditions. Qualitatively, the previous results are confirmed, but it is shown that any *oscillatory* convective motion must of necessity decay.

The above results might apply to a portion of the orogenetic shell if it is considered to be a plane. The macrocosmic case of the whole shell has been studied theoretically with special reference to geophysics by Pekeris (1935). The fluid was again assumed to be of Newtonian type. The pattern obtained was also a series of closed vortex tubes all around the shell (see Fig. 9).

It is impossible that turbulence occurs in viscous flow if either R is of the order of several thousand or λ above 45000. Turbulence always originates from the boundaries of the liquid and dissipates into its interior. The most marked feature of any sort of turbulence is that it is unsteady and quickly changing its pattern. It often does not show any regular feature and is only manageable by statistical methods.

PLASTIC FLOW: Much less is known about heat transfer in flowing plastic materials than in Newtonian liquids. We know of no case where a problem of plastic heat transfer has been exactly solved.

Therefore, we shall examine first what is

known about the flow patterns of plastic materials (which is little enough), and then try to combine it with thermal considerations.

The St. Venant body, as is readily seen, is too restricted for a sensible "plastodynamics", so the more general case of the Bingham body will be considered. The law of motion for such a Bingham body (Bingham, 1926) is:

$$dv/dr = \mu(\tau - \vartheta)$$

where τ is the shear stress, ϑ the St. Venant yield stress, dv/dr the velocity gradient and μ a constant of the material, called the mobility (reciprocal viscosity). The St. Venant body would have infinite mobility. For statical considerations, however, this was immaterial and therefore in the theory of plastic yield it is sufficient to consider a St. Venant body. For vanishing yield stress, the Bingham law reduces to the equation of motion for a Newtonian liquid.

The existence of the yield stress means that the motion does not depend only on the dimensionless numbers listed before. If the heat transfer is disregarded, the Reynolds number is still important (where μ is now replaced by $1/\eta$). Another important number is, however,

$$S = \vartheta D\mu/V$$

of which a fuller account is given by Oldroyd (1947b).

It may sometimes be necessary to apply more complicated laws of motion. The mobility is not always constant; it may increase when greater stresses are applied. Reiner (1930b) reviewed the possible laws of flow for plastic materials and stated the most general law consistent with our present knowledge of the phenomena and having the simplest algebraic form. But even so, it is rather complex and not too practical.

Very little has yet been done in solving specific problems which might have a bearing upon geophysical problems. Reiner (1930a) calculated the plastic flow between two rotating cylinders. If the inner cylinder rotates and the outer one is fixed, then that gives a very rough picture for part of a convection tube.

Reiner made his calculations under the assumption of the Bingham law of motion, for a fixed inner and rotating outer cylinder (a rotation viscosimeter). The material between the two cylinders will not flow if the torque M acting between the cylinders is smaller than a certain value M_0. If M exceeds the value M_0,

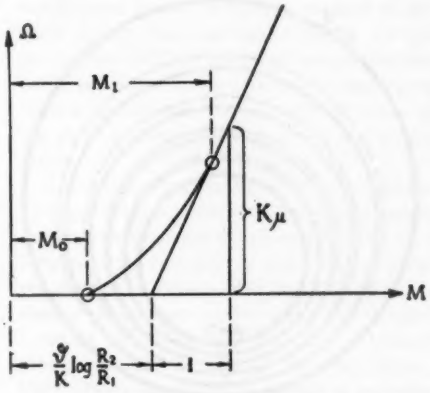


FIGURE 10.—CONNECTION BETWEEN THE TORQUE AND THE ANGULAR MOMENTUM IN REINER'S ROTATION VISCOSIMETER

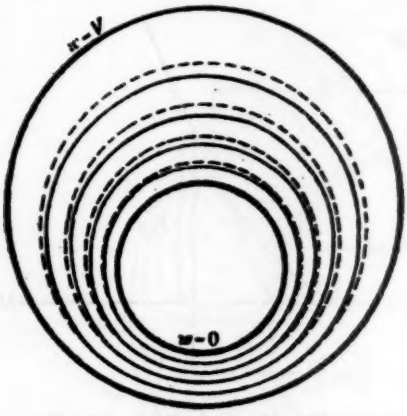
(After Reiner)

the material will start to flow where the stress is largest, i.e. at the surface of the inner cylinder. As long, however, as the stress on the inner surface of the outer cylinder is below ϑ, there will be a shell of solid material adjacent to the outer cylinder. When the torque becomes greater than another definite value M_1, all the material between the cylinders will flow. The connection between the torque M transmitted between the two cylinders and the relative angular velocity Ω is shown in Figure 10. K is a certain geometrical constant. The velocity distribution between the cylinders was also calculated. It takes the form of a rather complicated expression.

In order to obtain a better idea about the mechanics of plastic flow, more qualitative arguments have to be used. An interesting study of possible analogies between plastic and viscous flow has been given by Oldroyd (1947c). The plasticity equations are solved "in the large" for cylinders of various shapes moving through each other. The plastic lines of flow are compared with the viscous lines of flow (*see* Fig. 11). The difference is not very great, apart from the fact that in plastic flow one finds a

solid kernel in those regions where in viscous flow there is a small velocity gradient.

It is now our task to obtain an idea of what may happen when a plastic material is heated from below. For vanishing yield stress, the Bingham body is a Newtonian liquid. The presence of a yield stress will affect the formation of convection cells to such an extent that it will need a greater temperature difference to start the motion than that one corresponding to a characteristic product of Grashoff and Prandtl numbers equal to 1709. Moreover, in view of Oldroyd's results, it is very likely that the center of the vortex tube in the cell will rotate as a solid. The velocity distribution and the transmission of torques in the plastic region would be similar to that one in Reiner's rotation viscosimeter.



Contours of equal velocity in steps of 0·2V for Bingham material. Broken lines indicate the corresponding contours for a Newtonian liquid.

FIGURE 11.—COMPARISON OF PLASTIC AND VISCOUS LINES OF FLOW IN A SPECIAL CASE (After Oldroyd)

If the yield stress is assumed to be rather large, however, the above arguments are questionable. A new phenomenon may take place whose nature may not be revealed by such simple analogies. For large velocity gradients, a phenomenon might be found in the study of plastic flow which would be analogous to turbulence in a Newtonian liquid: The flow should become unstable instead of being steady and laminar. Phenomena of this sort are important in the pipe-line transportation of certain materials and therefore attempts have been made to find criteria for the onset of turbulence in plastic flow. Hersey (1932) used the method of dimensional analysis to find such criteria. His investigations were made for the general law of motion of Reiner and his equations contain many unknown functions. Even if his equations are reduced to Bingham's law, some unknown functions are still left so that Hersey's criteria are of very little practical use, except that for vanishing yield stress his equations reduce to Reynolds' criterion, which is thereby confirmed.

Thus, it must be expected that, under very great temperature differences, vortices would be formed at the boundaries which would dissipate into the plastic medium, as this was the case in viscous liquids. The flow is then no longer steady.

Further mathematical investigations of the theory of plastic flow must therefore be made before more can be said about convection currents in plastic material.

Geological Implications

General statement.—In considering those theories of orogenesis which assume a fluid mechanism in the orogenetic shell, we shall use the two review articles of Gutenberg (1930; 1939) and some more recent original papers.

As already mentioned, there are three distinct hypotheses falling into the present chapter: the undation, the continental drift, and the convection current hypotheses.

Undation theory.—This theory of Haarmann's (1930) assumes the earth to be a rotating mass of rather liquid material with a stiff coating. In the rhythmic occurrence of cosmic influences, the figure of the geoid is disturbed and has to be restored to equilibrium by the displacement of large masses, especially of subcrustal magma. The displacement of these subcrustal masses effects a vertical movement of the surface of the earth which shows up as the formation of mountains and geosynclines. After the disappearance of the cosmic perturbation, the motion of the crust will be in the

opposite direction, so that it starts to oscillate or undate up and down during the ages.

The undation theory has generally not been taken very seriously. We have mentioned above that Van Bemmelen and Berlage (1935) have investigated a model of the undation hypothesis and concluded that the theoretical frequency and also the damping ratio of the oscillations are both much too high. It is also very questionable whether the notably small cosmic perturbances can suffice to initiate large-scale mass displacements, unless some consideration about resonance frequencies are made. Such investigations, however, do not seem to have been undertaken. However, Van Bemmelen supports the undation theory and used it as a basis for explaining the geology of the Netherlands East Indies (Van Bemmelen, 1949). Many geologists who have worked in that region, though, do not support his interpretations.

Continental drift theory.—This theory assumes the whole earth to be practically liquid, with the land masses floating upon it in perfect local isostasy like ice on water. The fluid substratum is supposed to assume the equilibrium form of a geoid. As already shown, any floating masses upon such a rotating geoid trend to drift towards the equator. Wegener (1924), especially has stated the case for this hypothesis. It has been discussed subsequently on several occasions, but because of serious difficulties it is now almost abandoned.

A most serious difficulty is that all drift theories can explain only *one* orogenetic diastrophism. If two continents are drifting towards the equator for example, they may proceed until they collide. This can explain the folding of, say, the Alpide mountains, but once the continents have arrived at the equator, they would simply stay there and nothing more would happen, nor could anything have happened before they arrived at the equator. The diastrophisms of the Paleozoic era and of the Precambrian thus remain totally unaccounted for.

Secondly, the idea of local isostasy does not appear to be well supported. Modern gravity determinations have shown that mountain ranges and island arcs are not locally isostatically compensated. This does not fit very well into the concept of floating continents.

Thirdly, the origin of those floating continents is a problem. It is indeed somewhat questionable whether a crystallization of the magma would have produced continental blocks. One would imagine that the freezing would have formed a uniform coating of the earth rather than continental blocks. To get around this difficulty one must assume that the earth proceeded to cool faster in some spots than in others; one would naturally think of the poles as being cooler than the rest of the planet.

If this is assumed, however, then convection currents in the substratum must have occurred and two original continents would have been formed at the two poles in agreement with the calculations of Pekeris (Fig. 9). Such two continents have been postulated and named Laurasia and Gondwanaland. In a modern attempt at the continental drift hypothesis, Hills (1947) has tried to obtain a coherent theory of the present distribution and shape of continents and mountain belts. However, since the present distribution of the mountain belts is very irregular, he had to break up and shift Laurasia and Gondwanaland about in a rather arbitrary way. It is not at all clear where the forces for this shifting are supposed to have come from.

Large continental shifts have been postulated before, always with the understanding that the "collisions" gave rise to the mountains. The search for the forces led to the postulate of subcrustal convection currents (Holmes, 1929) whose drag would have enough power to throw the continents together in such a manner that mountains would be folded up. However, the old objection that only single orogenetic diastrophisms could be explained in this way still holds. Precambrian geologists everywhere agree that the shields are not parts of a primitive crust, but that they probably represent the fusion of old mountain belts, and certainly that they contain many belts of infolded sedimentary rocks.

The idea of continental collisions was therefore finally abandoned and the claim made that convection currents alone would suffice to explain the orogenetic cycles.

Convection currents.—Griggs (1939) and Vening Meinesz (1934; 1947; 1948) especially have

advanced the case for mountain building by means of convection currents.

Griggs (1939) assumes that convection takes place in the asthenosphere due to a temperature gradient within the latter. To demonstrate the effect of those postulated currents in relation to orogenesis, a model experiment was performed. The vortex tubes were replaced by rotating drums in a viscous liquid (Fig. 12). A more theoretical investigation of the orogenetic significance of those vortex tubes has been given by Hafner (1951). His results are similar to those of Griggs.

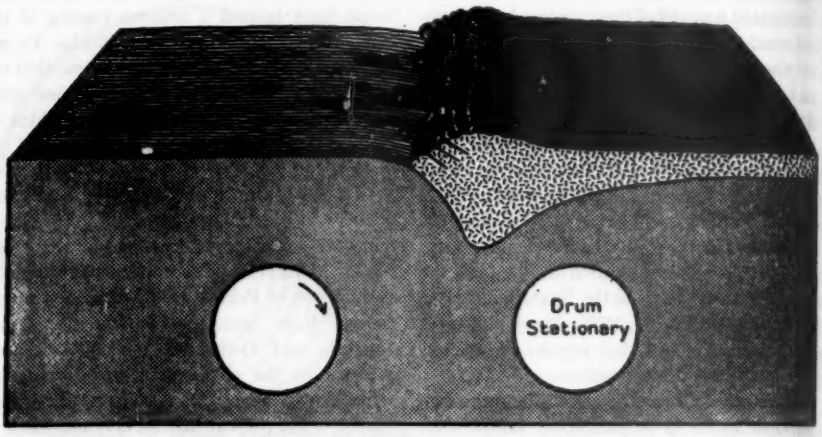


FIGURE 12.—STEREOGRAM OF A MODEL EXPERIMENT WITH A ROTATING DRUM IN A VISCOUS LIQUID
Showing the development of tectogenes. (After Griggs)

Thus, one is led to expect mountains and tectogenes along the "borderline" of a convection current, and such convection currents seem at first sight to provide a reasonable explanation for the mountains. However, there are some severe difficulties to be overcome before such a theory can be accepted.

Griggs' paper deals only with convection currents of continental dimensions or with the cross sections of mountain belts. The plan and the three-dimensional arrangement of convection currents in existing island and mountain arcs is completely neglected. Convection currents, as suggested by Griggs, form big vortices, and it has been demonstrated that a vortex line in any fluid is always closed or else ends at the surface or at the walls of the container. The rotating drums in the model experiment of Griggs form such vortex lines and the question arises, therefore, as to how the corresponding lines are arranged within the earth. If they are connected with curved island arcs, they must be curved, too, and where the island arcs join each other the vortex lines must disappear suddenly. From the hydrokinematical standpoint this is, to say the least, very difficult to explain.

Second, in Griggs' model, the dynamical similarity has been obtained by using equal Reynolds numbers, but the thermal similarity has been completely neglected. To start convection currents, the product of Grashoff and Prandtl numbers must be at least 1709. A little calculation shows that this is possible in the *earth* (for approximately $D = 500$ kms, $\rho = 3$ g/cm^3, $\beta = 5 \times 10^{-6}$/deg., $c = \frac{1}{4}$ cal/g.deg., $\eta = 10^{22}$ Poise and $k = 5 \times 10^{-3}$ cal/sec.cm.deg., one obtains $\lambda = 3000$), but the thermal facts have no analogues whatsoever in the *model*. It is questionable, therefore, whether the convection currents would occur in the supposed way.

Third, the convection currents described above are laminar and steady and thus do not reflect the fact that orogenetic events occur in single diastrophisms and not steadily. Griggs was fully aware of this difficulty and therefore

postulated that his substratum be pseudoviscous instead of viscous. It is not quite clear what he meant by the word "pseudoviscous" In the few calculations which he made, a rheological equation was used which resembles a creep condition of a Maxwell liquid, but the model which he constructed appears to show the characteristics of a St. Venant yield stress. At any rate, the idea was to introduce a substratum of such properties that it behaved like a solid until a sufficiently high temperature gradient was reached, and then executed a half revolution in laminar viscous motion. It then should stop dead, because the temperature gradient had been abolished by this process and not until a sufficient gradient had again been established was another cycle to start. Needless to say, the existence of such a mysterious pseudoviscous medium is purely speculative. The motion of plastics which may be related to Griggs' pseudoviscous motion will be discussed at the end of this section in greater detail, but they do not seem to behave as postulated by Griggs for his pseudoviscous material.

Therefore, the only way to obtain single diastrophisms in viscous liquids may be to abandon laminar motion and assume turbulence. In order to have turbulent motion, either the Reynolds number must be of the order of several thousand, absolutely impossible in the asthenosphere (the motion is at any rate much too slow), or else the characteristic product of Grashoff and Prandtl numbers must exceed 45,000. The latter condition could be satisfied if one assumes the viscosity of the orogenetic shell as low as 10^{21} Poise—which is unlikely although not impossible.

Thus we shall consider for a moment the possibility of unsteady flow. This sort of flow is quickly changing its pattern and thus could give rise to single orogenetic diastrophisms that occur repeatedly, but, it seems, much too frequently if turbulent motion of the substratum is assumed as cause. The idea that a *single* vortex may proceed towards the exterior of the earth and cause there spiral-shaped structures, as is known of the sunspots or the air in cyclones, has been promoted by Fujiwhara and coworkers (1933). Again, this hypothesis seems rather far fetched, for the echelon structures of Asia (which serve as an example in that paper) do not seem to have much actual resemblance with the cross section of a vortex tube.

Therefore, if one does not want to assume turbulence, one has to look for a different mechanism which could produce single diastrophisms, similar to the way Griggs tried to solve the problem. It is to the credit of Vening Meinesz (1948) that he stated clearly that he expected such an explanation by assuming a *plastic* substratum with a definite, nonvanishing yield strength.

Vening Meinesz supposed that a direct consequence of this finite yield strength would be the counteraction of the instability which otherwise the cooling of the earth would bring about. He considered that this cooling causes a lowering of the temperature at the surface of the convection layer, the upper part of this layer thus acquiring a greater density than the lower half. Vening Meinesz then proceeds to state that

"in the case of a Newtonian liquid, this would mean instability, as the slightest disturbance would start a convection current. If, however, the layer possesses a certain strength, the disturbance must be powerful enough to overcome this strength before the current can be started."

In this connection, the reader is reminded of the investigations of Jeffreys (1928) and others (Schmidt and Milverton, 1935; Schmidt and Saunders, 1938). In view of those results, the statement of Vening Meinesz that an arbitrarily small temperature gradient would mean instability in a viscous medium is not true. The temperature gradient has to reach a definite value even in viscous media before instability occurs. The additional assumption of a finite yield strength therefore, does not seem so tremendously important except to increase the temperature gradient necessary for instability.

Furthermore, Vening Meinesz believes that some other starting phenomenon is also necessary to get the currents moving and that a plastic substance would cause the currents to be intermittent. He proceeds with the following statement.

"Because of the initial temperature difference needed to overcome the strength limit and start the current, we may assume that this will quickly

attain a fairly high speed in comparison with that which a steady convection in a Newtonian liquid would assume. Moreover, during the first quarter of a complete revolution it will no doubt further accelerate, since the sinking column will receive more and more low temperature matter from the surface while in the rising column the higher temperature of the deeper layers penetrates further towards the surface. So the difference of mass in the two columns caused by their different temperatures will increase till a maximum is reached after about a quarter revolution. This increasing mass difference will produce an increasing pressure difference, with a resultant acceleration of the current during this period. (. . .) After about a quarter revolution the speed will gradually decrease as higher temperature matter penetrates from above into the sinking column and lower temperature matter from below into the rising column. The mass difference between the two columns will be thereby diminished and the current brought gradually to a stop. This must occur before a half revolution is made, since at that point, roughly speaking, the higher temperature matter has arrived in the upper layer and the cooler matter at the bottom; the situation has become stable. No new current can come into being before, first, the cooling of the earth has reestablished a vertical gradient of the temperature, and, second, a starting phenomenon of sufficient intensity has occurred."

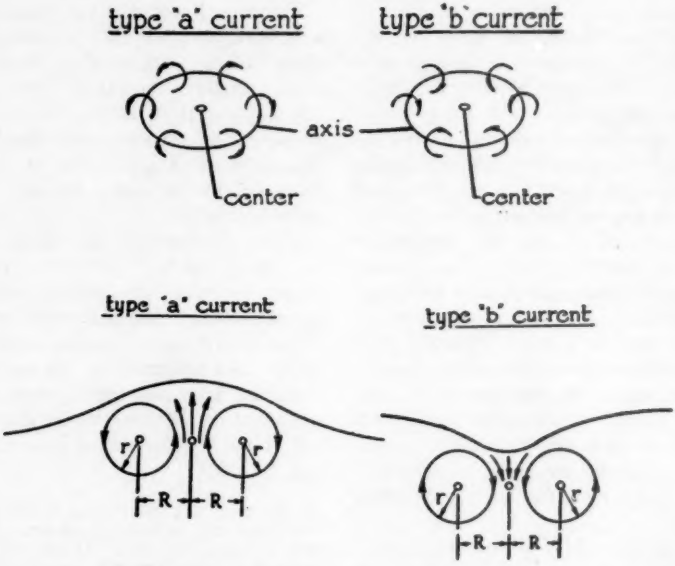


FIGURE 13.—THE TWO POSSIBLE TYPES OF CONVECTION CURRENTS
(After Scheidegger)

The assumption of a plastic substratum is thus believed to give rise to "intermittent" currents. The picture created by Vening Meinesz is, however, very phenomenological and not based upon sound rheological reasoning.

We have tried to obtain an idea of what happens when a plastic material is heated from below (under "Flow of Matter and Heat"). Although an exact solution of the problem admittedly does not exist, the evidence seems to point toward a steady phenomenon, not too much different from convection in a viscous material. Therefore, Vening Meinesz' suppositions need, to say the least, a lot more physical corroboration.

It seems that an intermittent phenomenon in plastics could only occur under turbulent conditions, and it is questionable whether these conditions apply in the earth. Thus, all the convection hypotheses outlined seem to face the serious difficulty that they can explain only steady phenomena of long duration.

On the other hand, the convection hypotheses have the great advantage of explaining the observed heat flow through the surface of the earth. Bullard (1950) held that this heat flow

could not be maintained very well merely by conduction through the outer mantle. Furthermore, convection currents in the iron core of the earth are believed to be the cause of the earth's magnetic field (Elsasser, 1950). To maintain those currents, a certain heat flow is necessary, a heat flow which cannot be maintained by conduction alone in the outer mantle. This serves to substantiate the observed data about heat flow out of the earth which, regarded by themselves, are rather inaccurate and might be changed by new measurements.

It seems, therefore, that such convection currents could exist only on a continental scale. There is no difficulty in assuming slow convection currents (Scheidegger, 1952a), provided that they move at a rate of not more than about 2 mm per year, which are quite sufficient to remove enough heat from the core to maintain the earth's magnetic field. Breaking strength and "viscosity" of the flowing material are about those of limestone.

Such convection currents must have one of the patterns shown in Figure 13. They might have geological significance in two ways. First, the type *a* currents might bring to the surface, sial which accumulates in rigid shields above these rising columns (Fig. 14). Alternatively (less likely), the sial at the surface might be concentrated in shields by the type *b* currents without being engulfed and sucked down by them. Both cases would cause physiographic features of a continental scale. If the radius *R* of convection currents becomes too big, ring-shaped structures result.

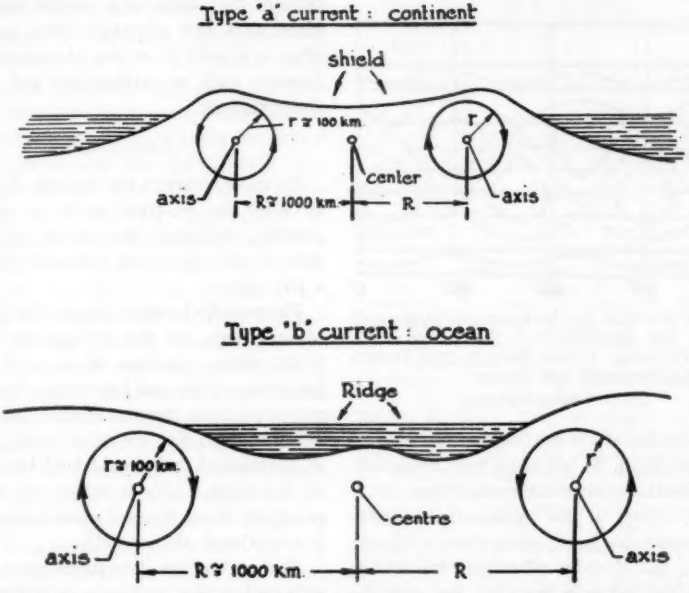


FIGURE 14.—POSSIBLE FORMATION OF CONTINENTS AND OCEANS BY UNDERLYING CONVECTION CURRENTS
(After Scheidegger)

In this manner, convection currents might provide an explanation of the existence of continents and oceans. They would also provide an explanation of why all continental and ocean shields are of the form of blocks—and not a large belt around the globe. The motions connected with these convection currents would be the continental uplift, the drag at the edges of a continent, etc. These motions would be of the same order of speed as the convection currents—a few millimeters per year. A drawback,

however, is that all shields seem to show the structure of eroded mountain roots rather than of uplifted blocks of magma.

Vening Meinesz (1944) has speculated that continental convection currents might explain

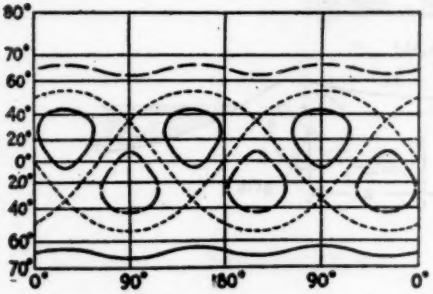


FIGURE 15.—MAP (ON MERCATOR'S PROJECTION) SHOWING THE HYPOTHETICAL SYSTEM OF CONVECTION CURRENTS GIVING RISE TO THE DISTRIBUTION OF CONTINENTS AND OCEANS
(After Vening Meinesz)

the distribution of the continents over the surface of the earth. As has often been remarked, the distribution of the continents, though quite irregular, shows a few systematic features. The continents are nearly everywhere antipodic to oceans, and they are all roughly triangular, touching each other in the north and pointing southwards. Four old shields have their positions, roughly speaking, at the corners of a tetrahedron.

This distribution of the shields might be explained by speculating that there is or was at one time a system of large convection currents in the earth, the centers of four type *a* currents coinciding with the corners of a tetrahedron with the centers of four type *b* currents opposite to those corners. Figure 15 shows the system of currents: the axes of type *a* currents are represented by solid lines; of type *b* currents by broken lines. Each current covers an octant whose edges are indicated by dotted lines.

The creation of this system could be made plausible by the remark that a regular pattern is most likely to occur. The octahedron is the only regular surface in which an even number of sides touches in one corner, and this is a necessary condition for a convection current distribution.

Thus, it seems quite plausible that the hypothesis of convection currents might be capable of explaining the observed heat flow and physiographic phenomena that occur steadily and on a continental scale. The hypothesis, however, seems rather shaky when applied to features that occur on a smaller scale such as island arcs and mountain belts, and equally when it is used to explain phenomena of short duration such as earthquakes and orogenetic diastrophisms.

CONCLUSION

We have reviewed the theories of orogenesis. In doing so, we tried to be as impartial as possible, discussing the merits and faults of each of the hypotheses from the viewpoint of a physicist.

The principal competitors as the true theory of orogenesis are the contraction hypothesis (with sliding fracture along arcs) and the hypothesis of thermal convection. Both theories are based upon the assumption that the earth is losing heat. (On the other hand, the theory of continental drift would hold for any model of the earth which is sufficiently fluid independently from thermal considerations, but it is now almost abandoned.)

The contraction hypothesis gives a reasonable explanation for the shape of the island arc and mountain belts, for the earthquakes, and for the fact that orogenesis occurs in single diastrophisms. However, the observed heat flow appears too large. Furthermore, an investigation of the creep properties of rock (even of sandstone) shows that such material is capable of slow flow, which, naturally, tends to counteract any build-up of stresses and thus also the occurrence of earthquakes and orogenetic diastrophisms.

The convection theory shows that the very properties of creep and flow might cause the mountain belts and island arcs as well as the continents, and explains the observed heat flow at once. However, only cross sections of orogenetic belts have been explained satisfactorily. Neither their arcuate strike nor the deep focus earthquakes connected with them are explained. The repeated but intermittent nature of orogenetic movements is another difficulty in this theory.

Both the two principal theories, thus, seem

able to account for part of the observedphenomena. Heretofore, it has always been assumed that the two theories preclude each other. This is, however, not necessarily the case. The mechanism that produces island arcs, mountain belts, and earthquakes may be different from the mechanism causing the heat flow and movements on a continental scale. The two phenomena—thermal convection currents and sliding fracture—could exist side by side if the characteristic time for the convection is long compared with the characteristic time for the fractures—in other words, if the movements around the island arcs are measured at least in centimeters per year, as compared with the few millimeters per year necessary to account for the heat flow by convection.

Thus, a combination of the two theories might in the end provide a satisfactory explanation for the observed patterns. However, it should be kept in mind that all the theories of orogenesis remain purely speculative until more factual data about our planet are known. The question as to whether the earth is heating or cooling is most fundamental and has not been decided yet. The directions of motion of the deep focus earthquakes is known for only one or two cases which are hardly conclusive. Finally, it might be hoped that some day one will be able to get really substantial information about the rheological state of the earth's interior.

As long as we are so much in the dark about these fundamental facts, we can hardly arrive at more than rather vague conclusions as to the cause of orogenesis.

References Cited

Benioff, H. (1949) *Seismic evidence of the fault origin of oceanic deeps*, Geol. Soc. Am., Bull., vol 60, p. 1837–856.

Bingham, E. C. (1926) *An investigation of the laws of plastic flow*, U. S. Bur. Standards, Bull., vol. 13, p. 309–353.

Bullard, E. C. (1950) *The heat transfer from the core of the earth*, Royal Astron. Soc. London, Monthly notices, Geophys. Suppl., vol. 6, p. 36–41.

Coulomb, J. (1943) *Une interprétation simultanée des séismes profonds et des bandes d'anomalies de la pesanteur*, Acad. Sci., C.R., vol. 217, p. 355–356.

— (1945) *Séismes profonds et grandes anomalies de la pesanteur*, Ann. Géophysique, vol. 1, p. 244–255.

Elsasser, W. M. (1950) *The earth's interior and geomagnetism*, Rev. Mod. Phys., vol. 22, p. 1–35.

Eötvös, R. v. (1910) *Bericht über geodätische Arbeiten in Ungarn, besonders über Beobachtungen mit der Drehwaage*, Assoc. Geod. Inter. 16th Int. Conf., C.R., vol. 1, p. 319–350.

Ertel, H. (1931) *Zur Analyse der Polfluchtkraft*, Gerl. Beitr., vol. 32, p. 38–46.

—— (1935) *Die Berechnung der Polfluchtkraft*, Gerl. Beitr., vol 43, p. 327–330.

Freudenthal, A. M. (1950) *The inelastic behavior of engineering materials and structures*, John Wiley, New York.

Fujiwhara, S.; Tsuijimura, T., and Kusamitsu, S. (1933) *On the earth-vortex, echelon faults and allied phenomena*, Erg. kosm. Physik, vol. 2, p. 303–360.

Geszti, J. (1929) *Zusammenschub der Erdrinde*, Gerl. Beitr., vol. 21, p. 36–78.

Goldstein, S. (1938) *Modern developments in fluid dynamics*, 2 vols. Clarendon Press, Oxford.

Griggs, D. (1939) *A theory of mountain building*, Am. J. Sci., vol. 237, p. 611–650.

Gutenberg, B. (1930) *Geotektonische Hypothesen*. Handbuch der Geophysik, vol. 3, p. 442–547.

—— (1939) *Internal constitution of the earth*, McGraw-Hill, New York, 413 pp.

Haarmann, E. (1930) *Die Oszillationstheorie*, Verl F. Enke, Stuttgart, 260 pp.

Hafner, W. (1951) *Stress distribution and faulting*, Geol. Soc. Am., Bull., vol. 62, p. 373–398.

Hencky, H. (1923) *Ueber einige statisch bestimmte Fälle des Gleichgewichtes in plastischen Körpern*, Z. ang. Math. u. Mech. vol. 3, p. 241–251.

Hersey, M. D. (1932) *Dimensional analysis of plastic flow*, Jour. Rheol. vol. 3, p. 23–29.

Hill, R. (1950) *The mathematical theory of plasticity*, Oxford Univ. Press, 356 p.

Hills, G. F. S. (1947) *The formation of the continents by convection*, Edw. Arnold & Co., London, 102 p.

Holmes, A. (1929) *A review of the continental drift hypothesis*, Mining Mag., vol. 40, p. 205–9, 286–8, 340–7.

Jeffreys, H. (1926), *The stability of a layer of fluid heated from below*, Phil. Mag., ser. 7, vol. 2, p. 833–844.

—— (1928) *Some cases of instability in fluid motion*, Royal Soc. Pr., ser. A, vol. 118, p. 195–208.

—— (1929) *The earth*, 2nd ed., Cambridge Univ. Press, London. 346 p.

Koning, L. P. G. (1942) *On the determination of the fault-planes in the hypocentre of the deep-focus earthquake of June 29, 1934 in the Netherlands East Indies*, K. Ned. Akad. Wet., Pr., vol. 45, p. 636–642.

Lake, P. (1931a) *Island arcs and mountain building*, Geog. Jour., vol. 78, p. 149–160.

—— (1931b) *Mountain and island arcs*, Geol. Mag., vol. 68, p. 34–39.

Lamb, H. (1932) *Hydrodynamics*, 6th ed., Cambridge Univ. Press, London, 738 p.

Leutert, W. (1948) *Die erste und zweite Randwert aufgabe der linearen Elastizitätstheorie für die Kugelschale*, Swiss Federal Inst. Technol., Zürich, Thesis.

Love, A. E. H. (1927) *A treatise on the mathematical theory of elasticity*, 4th ed., Cambridge Univ. Press, London, 643 p.

Low, A. R. (1929) *On the criterion for stability of a*

layer of viscous fluid heated from below. Royal Soc., Pr., ser. A, vol. 125, p. 180–195.

McAdams, W. H. (1942) *Heat transmission*, 2nd ed., McGraw-Hill, New York.

Mohr, O. (1928) *Abhandlungen aus dem Gebiete der technischen Mechanik*, 3. Aufl., Verl. Wilh. Ernst und Sohn, Berlin, 622 p.

Nadai, A. (1924) *Ueber die Gleit- und Verzweigungsflächen einiger Gleichgewichtszustände bildsamer Massen und die Nachspannungen bleibend verzerrter Körper*, Z. Physik, vol. 30, p. 106–138.

—— (1931) *Plasticity*, McGraw-Hill, New York, 348 p.

—— (1933) *Theories of strength*, Am. Soc. Mech. Eng., Tr. vol. 55, sec. Jour. Applied Mech., p. 111–129.

Oldroyd, J. G. (1947a) *A rational formulation of the equations of plastic flow for a Bingham solid.* Cambridge Philos. Soc. Pr., vol. 43, p. 100–105.

—— (1947b) *Two-dimensional plastic flow of a Bingham solid.* Cambridge Philos. Soc., Pr., vol. 43, p. 383–395.

—— (1947c) *Rectilinear plastic flow of a Bingham solid*, Cambridge Philos. Soc. Pr, vol. 43, p. 396–405, 521–532.

Pekeris, C. L. (1935) *Thermal convection in the interior of the earth*, Royal Astron. Soc., Monthly Notices, Geophys. Suppl., vol. 3, p. 343–367.

Pellew, A. and Southwell, R. V. (1940) *On maintained convective motion in a fluid heated from below*, Royal Soc. Pr., ser. A., vol. 176, p. 312–343.

Prager, W. (1946) *The general variational principle of the theory of structural stability*, Quart. Applied Math., vol. 4, p. 378–384.

—— (1948a) *Plasticity for the aerodynamicist*, Jour. Aeronaut. Sci., vol. 15, p. 253–262.

—— (1948b) *The stress-strain laws of the mathematical theory of plasticity*, Am. Soc. Mech. Eng., Tr., vol. 70, sec. Jour. Applied Mech. (15), p. 226–233.

Reiner, M. (1930a) *The theory of plastic flow in the rotation viscosimeter*, Jour. Rheol., vol. 1, p. 5–10.

—— (1930b) *The general law of flow of matter*, Jour. Rheol., vol. 1, p. 11–20.

—— (1949) *Twelve lectures on theoretical rheology*, North-Holland Pub. Co., Amsterdam, 162 p.

Ruud, I. (1938) *Tektonische Hauptprobleme im Lichte neuerer Materialforschung*, Gerl. Beitr., vol. 52, p. 123–169.

Sadowski, A. (1943) *A principle of maximum plastic resistance*, Am. Soc. Mech. Eng., Tr., sec. Jour. Applied Mech. p. 65–68.

Scheidegger, A. E. (1952a) *Physical aspects of the convection current hypothesis of orogenesis*, Am. Geophys. Union, Tr., (in press).

—— (1952b) *Physical Aspects of the contraction hypothesis of orogenesis* Canadian Jour. Physics, vol. 30, p. 14–25.

—— and Wilson, J. T. (1950) *An investigation into possible methods of failure of the earth*, Geol. Assoc. Canada, Pr., vol. 3, p. 167–190.

Schmidt, R. J. and Milverton, S. W. (1935) *On the instability of a fluid when heated from below*, Royal Soc., Pr., ser. A, vol. 152, p. 586–594.

—— and Saunders, O. A. (1938) *On the motion of a fluid heated from below*, Royal Soc. Pr. ser. A, vol. 165, p. 216–228.

Schwerin, E. (1922) *Zur Stabilität der dünnwandigen Hohlkugel unter gleichmässigem Aussendruck*, Z. ang. Math. und Mech, vol. 2, p. 81–91.

Seigel, H. O. (1950) *A theory of fracture of materials and its application to geology*, Amer. Geophys. Un., Tr., vol. 31, p. 611–619.

Slichter, L. B. (1941) *Cooling of the earth.* Geol. Soc. Amer., Bull., vol. 52, p. 561–600.

Soderberg, C. R. (1938) *Plasticity and creep in machine design*, Timoshenko Anniv. vol., MacMillan, p. 197–210.

Sokolnikoff, I. S. (1946) *Mathematical theory of elasticity*, McGraw-Hill, New York, 273 p.

Stüssi, F. (1950) *Die Grundlagen der mathematischen Plastisitätstheorie und der Versuch*, Z. ang. Math. u. Physik vol. 1, p. 254–267.

Timoshenko, S. (1936) *Theory of elastic stability*, McGraw-Hill, New York, 497 p.

—— (1942) *Strength of materials*, (part II), D. van Nostrand, New York, 496 p.

Van Bemmelen, R. W. (1949) *The geology of Indonesia*, Government Printing Office, The Hague, vols. 1A, 1B, 2.

—— and Berlage, H. P. (1935) *Versuch einer mathematischen Behandlung geotektonischer Bewegungen unter besonderer Berücksichtigung der Undationstheorie*, Gerl. Beitr., vol. 43, p. 19–55.

Vening Meinesz, F. A. (1934) *Gravity and the hypothesis of convection currents in the earth*, K. Ned. Akad. Wet. Pr., vol. 37, p. 37–45.

—— (1944) *De verdeeling van continenten en oceanen over het aardoppervlak*, K. Ned. Akad. Wet., Versl., vol. 53, no. 4

—— (1947) *Convection currents in the earth*, K. Ned. Akad. Wet., Pr., vol. 50, p. 237–245.

—— (1948) *Major tectonic phenomena and the hypothesis of convection currents in the earth*, Geol. Soc. London, Quart. Jour. vol. 103, p. 191–207.

Wegener, A. (1924) *The origin of continents and oceans.* Translated from the 3d. German ed. by J. G. A. Skerl. Methuen, London, 212 p.

Wilson, J. T. (1949) *An extension of Lake's hypothesis concerning mountain and island arcs*, Nature, vol. 164, p. 147–8.

—— (1950) *An analysis of the pattern and possible cause of young mountain ranges and island arcs*, Geol. Assoc. Canada Pr., vol. 3, p. 141–166.

—— (1951) *On the growth of continents;* Royal Soc. Tasmania, Papers & Pr. 1950, Hobard, p. 85–111

Zoelly, R. (1915) *Ueber ein Knickungsproblem an der Kugelschale*, Swiss Federal Inst. Technol. Thesis. Zurich,

IMPERIAL OIL LTD., PRODUCING DEPARTMENT, 300 NINTH AVE. WEST, CALGARY, ALBERTA, CANADA.

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, AUGUST 2, 1951.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 64, PP. 151–196, 4 FIGS., 4 PLS. FEBRUARY 1953

GEOLOGY OF AGUA FRIA QUADRANGLE, BREWSTER COUNTY, TEXAS

BY C. GARDLEY MOON

ABSTRACT

The 15-minute Agua Fria quadrangle in southwestern Brewster County, Texas, is arid, sparsely vegetated, and includes diverse topographic features that result chiefly from complex structure and variation in rock resistance to erosion. The mountainous and more complicated southern part of the area has suffered much deformation by igneous intrusions and faulting.

The Comanche series is represented by the Devils River limestone, Grayson marl, and Buda limestone. A disconformity separates it from the overlying gradational Gulf series which consists of the Boquillas, Terlingua, and Aguja formations. Because the Boquillas-Terlingua boundary problem is critical and unsettled, lithologic members and paleontologic zones in that section are described in considerable detail. A distinctive 50-foot rock unit, herein named the Fizzle Flat lentil, occurs about the middle of the Boquillas-Terlingua sequence. A widespread angular unconformity separates the Gulf series from the Tertiary Buck Hill volcanic series. Quaternary terrace gravels occur at different levels, and other alluvial deposits have been mapped.

The Tertiary hypabyssal igneous rocks are alkalic and form stocks, laccoliths, plugs, sills, dikes, and bysmaliths or trap-door domes. Several lava flows are preserved in the southwest part of the quadrangle. Metamorphic effects generally are slight.

The area is part of the Big Bend sunken block. Except where influenced by intrusive masses, a pattern of northwesterly normal faults establishes the structural trend of the area. Step faults are common. Most of the major faults are downthrown to the southwest with the huge intervening blocks tilted gently to the northeast. That much of the fault pattern was established during the Laramide revolution and that faulting recurred along the old lines of weakness fairly late in Tertiary time are postulated.

CONTENTS

TEXT

	Page
Introduction	152
Field work	152
Acknowledgments	152
Previous work	153
Physiography	153
Stratigraphy	153
Stratigraphic units	153
Comanche series	153
Devils River limestone	153
Grayson (Del Rio) marl	154
Buda limestone	156
Gulf series	157
Tentative correlation	157
The Boquillas—Terlingua problem	157
Lower Boquillas—Terlingua unit	158
Upper Boquillas—Terlingua unit	163
Aguja formation	170
Tertiary	173
General description	173
Buck Hill volcanic series	173
Quaternary	184
General description	184
Gravel	184
Alluvium	184
Intrusive igneous rocks	184
Introduction	184
Trap-door domes	185
Stocks, laccoliths, bysmaliths, plugs, etc.	186
Sills	188
Dikes	188
Metamorphic effects	188
Igneous petrography	188
Structural geology	189
General description	189
Normal faults	191
Domes	192
Geologic history	192
Economic geology	194
References cited	194

ILLUSTRATIONS

Figure	Page
1. Index map of the southern part of Trans-Pecos Texas	152
2. Correlation of Gulf series in Agua Fria quadrangle	159
3. Trap-door dome, Gray Hill, and domical uplift, Packsaddle Mountain	186
4. Structural setting of the Agua Fria quadrangle	190

Plate	Facing page
1. Geologic map and structure sections of Agua Fria quadrangle, Texas	151
2. Boquillas—Terlingua sequence	164
3. Tuffs and topographic forms	165
4. Buck Hill volcanic series	182

TABLES

	Page
1. Petrography of the igneous rocks of the Agua Fria quadrangle, Texas	190
2. Estimated stratigraphic throw of several major faults	191

Introduction

The 15-minute Agua Fria quadrangle, an area of about 275 square miles in the southwestern part of Brewster County in the Big Bend region of Texas, is bounded by the 29°45′ and 29°30′ parallels and the 103°30′ and 103°45′ meridians (Fig. 1). The center of the quadrangle lies almost 60 miles south of the city of Alpine.

The area is arid and devoted to grazing. State highway No. 118, known as the Alpine-Terlingua road, traverses the eastern part of the quadrangle. There are few other good roads, but passable automobile trails have been bladed into remote ranch localities.

The investigation of the structure, stratigraphy, and igneous geology of the Agua Fria quadrangle is part of the large-scale mapping project and program of study that the Bureau of Economic Geology is conducting in west Texas.

Field Work

Field time, during 1947 and 1948, totalled 5 months. The geological data were recorded on aerial photographs and transferred to the U. S. Geological Survey topographic sheet of the Agua Fria quadrangle.

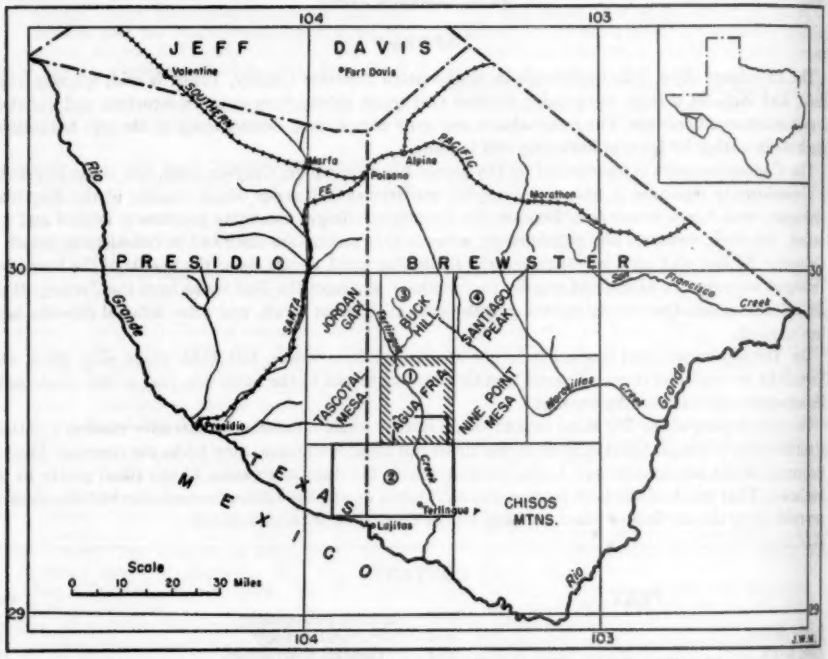


Figure 1.—Index Map of the Southern Part of Trans-Pecos Texas

Showing Agua Fria quadrangle (1) and adjoining areas of published maps: (2) Terlingua-Solitario region (Lonsdale, 1940); (3) Buck Hill quadrangle (Goldich and Elms, 1949); (4) Santiago Peak quadrangle (Eifler, 1943).

Acknowledgments

Credit is due so many individuals and organizations that only brief acknowledgments are given here, and others appear in the text.

Dr. John T. Lonsdale, Director of the Bureau of Economic Geology, suggested the problem and directed the work, and Dr. S. S. Goldich supervised the field program. Dr. L. W. Stephenson of the U. S. Geological Survey spent the month of August 1948 in the Big Bend region. His paleontological work was of material value in problems of stratigraphy. Faculty members

of the Geology and Petroleum Engineering Departments of The University of Texas and staff members of the Bureau made helpful suggestions and read and criticized the manuscript. Dr. J. A. Wilson identified the vertebrate material.

Robert B. Davis, J. Don Langston, and Mrs. Jule J. Moon were capable assistants, and the advice and cooperation of the ranchers expedited the field work.

Field and laboratory expenses were defrayed by the Bureau of Economic Geology and the Humble Oil and Refining Company Fellowship in Geology.

Previous Work

Hill (1900, p. 2) first listed the Trans-Pecos Province as a natural subdivision of the physical geography of the State. Udden (1907b) was the first to describe the stratigraphy. Where possible to determine, his definitions of formations in the Gulf series were followed in the present mapping.

Baker has published several papers on Trans-Pecos Texas that emphasize structure. Many data from his earlier works are included in his publications of 1935.

Lonsdale (1940), the first to concentrate attention on specific rock masses within the quadrangle, studied and mapped the igneous geology of the southern part of the area.

The Buck Hill volcanic series, defined by Goldich and Elms (1949) in the next quadrangle to the north, has been traced in the present work along the western third of the area.

Physiography

Great diversity in structural conditions and resistance of the rocks (clays to igneous types) and scant vegetation in this semidesert region provide a variety of topographic forms (Pl. 3; Pl. 4, fig. 1) ranging from valley flats to peaked mountains. The less spectacular features are generally found in the north; those resulting from more complex geological conditions are abundant in the south. The maximum relief, east of Agua Fria Mountain, is almost 1800 feet; the average elevation for the quadrangle is approximately 3500 feet.

Except for the extreme eastern part, where intermittent drainage is into Nine Point Draw, the Agua Fria area is drained by Terlingua Creek and its tributaries, the largest being Alamo de Cesario Creek. Terlingua Creek, which empties into the Rio Grande, is a large intermittent stream with a few permanent stretches and water-holes. The valley developed by it, depending upon rock erosional resistance, ranges from a broad open type to canyons and gorges. Several stream terraces occur along its course in the central part of the quadrangle.

Stratigraphy

Stratigraphic units

Quaternary		Alluvium
		Gravel
Tertiary		Buck Hill volcanic series
Cretaceous	Gulf series	Aguja sandstone
		upper Boquillas - Terlingua unit
		lower Boquillas - Terlingua unit
	Comanche series	Buda limestone
		Grayson (Del Rio) marl
		upper Devils River (= Georgetown) limestone

Comanche Series

Devils River limestone.—The Devils River limestone was named by Udden (1907a, p. 56–60) from exposures along Devils River in west Texas, where the section consists of resistant, white to gray, massively bedded limestone. These moderately coarse-grained to compact limestones are equivalent to the Edwards and Georgetown formations of central Texas. The upper Devils River is the oldest rock exposed in the Agua Fria area, and fossils indicate that it is of Georgetown age.

Outcrop: The Devils River limestone crops out on Gray Hill, Packsaddle Mountain, Panther Mountain, and the northeast flank of the Solitario in the extreme southwest corner of the area. These localities are structural highs with many faults of large displacement, and the resistant Devils River forms dip-slopes in the uplifts. At Gray Hill, the dip-slope is to the north-northwest; at Panther Mountain it is south-southeast; in the Solitario area, to the

northeast; and on Packsaddle Mountain it is very nearly quaquaversal. Fault scarps of the Devils River form precipitous cliffs in which are caves and shelters.

At Gray Hill and at Panther Mountain the Devils River is exposed in trap-door blocks of domical uplifts. Outcrops in the southwest part of the area occur in similar up-faulted blocks. The upper Devils River limestone at Packsaddle Mountain wraps around a rhyolite plug except on the north flank, where a fault of great magnitude interrupts its continuity.

THICKNESS AND LITHOLOGY: The greatest observed thickness of Devils River section is on the west side of the igneous plug that forms the core of Packsaddle Mountain, but complex structural conditions made a measurement impractical. Hence only the 180 feet of upper Devils River exposed at the south end of Gray Hill is described.

The lower 120 feet of this interval consists of very hard, gray to brownish-gray, massively bedded, almost pure limestone with a few zones of gray to rusty brown chert nodules. The massive beds form vertical cliffs, some of which are honeycombed to cavernous. The strata exhibit karren and a type of weathering which suggests that solution has taken place along minute irregular cracks. The tinahitas described by Udden (1907b, p. 28) characterize the weathered rock surfaces in this section, and the rock weathers into angular fragments.

Evenly bedded limestones 1 to 2 feet in average thickness make up most of the upper 60 feet of Devils River section. These strata are essentially the same color as the massive beds below except for a tendency toward lighter and even whitish shades for the uppermost beds. Being somewhat irregularly bedded, the topmost beds weather to nodules as well as angular fragments. On aerial photographs, a fluted pattern of weathering characterizes the top of the formation.

FOSSILS: Fossils collected from the Devils River on the north flank of Packsaddle Mountain include: *Ennalaster texanus* Roemer, *Holaster simplex* Shumard, *Kingena wacoensis* Roemer, *Gryphaea washitaensis* Hill, *Gryphaea* sp., *Pecten* (*Neithea*) *bellula*? Cragin, *Pecten* (*Neithea*) *texanus* Roemer, *Pecten* sp., a small *Nucula*-like pelecypod, and a small *Hamites*. At the top of the Devils River section on Gray Hill several large *Turrilites brazoensis* Roemer were found. Although some of the species listed have longer ranges, several are Georgetown fossils. Paleontologic evidence supports, therefore, the assignment of Georgetown age to the Devils River beds exposed in the area.

STRATIGRAPHIC RELATIONS: The contact of the Devils River limestone with the overlying Grayson marl is conformable. The base of the Devils River is not exposed in the Agua Fria quadrangle.

Grayson (*Del Rio*) *Marl.*—Cragin (1894, p. 40, 43) first used the term Grayson marl for numerous outcrops, especially in Grayson County, Texas, of the yellowish, highly calcareous, slightly arenaceous, fossiliferous marl that contains abundant *Exogyra arietina* Roemer. Hill and Vaughan (1898, p. 236) applied the name Del Rio clay to the greenish laminated clay, which weathers yellow and includes beds of limestone, in the vicinity of Del Rio, Val Verde County, Texas. Here the clay is underlain by Georgetown limestone and overlain by Buda limestone. Although the definition of Hill and Vaughan is more specific and fits precisely the stratigraphic sequence of the Agua Fria area, Cragin's Grayson has priority.

OUTCROP: Sandwiched between the massive limestones of the Devils River below and the Buda above, the Grayson marl crops out in the four uplifts listed for the Devils River formation. The uppermost Grayson is exposed at a fifth locality about 2 miles east-southeast of the Old Stage Stand (NE)[1] in the upthrown block of a fault of the same name.

THICKNESS AND LITHOLOGY: A 118-foot thick

[1] To aid in locating positions on Plate 1, the following scheme is used:

NW	NC	NE
WC	C	EC
SW	SC	SE

The Old Stage Stand (NE), for example, is found in the northeast 5-minute quadrangle of the map area.

Grayson section was measured on Gray Hill, but badly covered slopes prevented the exact determination of vertical positions of fossil zones.

The Grayson formation consists of friable, yellow-green-gray, laminated calcareous shale to massive calcareous clay or marl. The lower third of the section contains a few thin, rusty silt beds up to 2 inches thick. In the upper part, there are thin beds of impure (sandy), rusty brown limestone that contain countless *Haplostiche texana* (Conrad). A 2.5 to 3-inch bed of hard, rusty yellow-gray coquina, composed of tightly cemented fragments of oyster shells, occurs a foot below the Grayson-Buda contact.

Talus and slide rock conceal all except the uppermost part of the Grayson formation at the base of the fault scarp about 2 miles east of the Old Stage Stand. Laminated beds of hard, rusty brown, silty to sandy limestone, 3-6 inches thick, make up this section.

FOSSILS: *Exogyra arietina* Roemer, abundant in the middle Grayson of central Texas, is rare in the Agua Fria area. The diagnostic Grayson fossil in west Texas is the arenaceous foraminifer *Haplostiche texana* (Conrad), abundant in the upper sandy limestone beds.

Turrilites brazoensis Roemer and the oysters *Exogyra cartledgei* Böse and *Gryphaea mucronata* Gabb occur both above and below the Grayson-Buda contact. Other fossils found near the top of the Grayson section on Gray Hill are *Ennalaster texanus* (Roemer) and a *Gryphaea* similar to *G. washitaensis*.

STRATIGRAPHIC RELATIONS: Although the two formations differ markedly lithologically, no indication of unconformable relationships between the Grayson and the Devils River was noted. There is a thin transition zone in which the almost pure limestone of the Devils River grades upward into impure, marly, nodular limestone, and this grades into typical Grayson marly facies. The presence of *Turrilites brazoensis* Roemer in both upper Devils River and lower Grayson adds support to the evidence for a conformable contact.

Possible bore-holes and the oyster shell coquina near the top of the Grayson suggest a submarine break in sedimentation at the end of Grayson time.

Composite section of Comanche Cretaceous measured on Gray Hill from south to north and beginning east of north-south fence line

	Thickness Feet
Gulf Cretaceous	
Boquillas flags—	
11. Hard, gray to rusty red, thin-bedded and banded lower Boquillas flags of impure silty limestone with gritty feel. Flags weather to angular fragments. Thick growth of lechuguilla	2
—Disconformity—	
Comanche Cretaceous	
Buda limestone—	
10. Hard, creamy white to light-gray, unevenly bedded, relatively pure porcellaneous and brecciated limestone. Decrease in bed thickness from base to top. Uppermost strata 1.5–0.5 foot thick. Thin marly breaks and irregular nodules	69
—Diastem?—	
Grayson marl—	
9. Friable, yellow-green-gray, laminated to massive calcareous shales and clays. Several thin rusty silt beds, up to 2 inches thick, near base. Thin beds of impure rusty brown limestone plus innumerable *Haplostiche texana* (Conrad) in upper section. Hard, rusty yellow-gray coquina bed 2.5–3 inches thick, including specimens of *Exogyra* and *Gryphaea*, 1 foot below Buda contact. Internal molds of bore-holes (?) in top few inches	118
Devils River limestone—	
8. Resistant, gray to white limestone. Most of lower beds 1–2 feet thick with tendency toward more irregular bedding, lighter color, and nodular weathering upward. *Pecten* spp., *Kingena wacoensis* Roemer, and snail-like gastropods common	60
7. Two very hard limestone beds, each 1 foot thick, mark top of vertical cliff-forming section	2
6. Lithologically similar to unit below except cavernous, less honeycombed, and generally fewer fossils. Well-developed karren and fossil agglomerate mark top	

of this massive section. Chert zone with nodules up to 8 inches in diameter 18 feet above base of unit. Ocotillo and creosote bush common	51
5. Very hard, light-gray to brownish-gray, massively bedded, somewhat honeycombed limestone. Highly fossiliferous: silicified rudistids and a few *Pecten*	20
4. Very hard, light-gray to brownish-gray, very massively bedded, slightly honeycombed limestone. Two rather indistinct horizons marked by gray to rusty brown chert nodules up to 1.5 feet in diameter occur 4 and 6 feet above base of interval. Silicified fossils and more pronounced honeycombing in upper 9 feet. Karren weathering	17
3. Partly covered, very hard, gray, massively bedded limestone with karren and cracked weathering. Silicified fossils	30
2. Slope-covered interval of Devils River	100
1. East-west road in valley flat.	
Total upper Devils River exposed	180

Buda limestone.—Vaughan (1900, p. 18) substituted the name Buda limestone for the preoccupied Shoal Creek limestone as defined by Hill in 1889. At the type locality along Shoal Creek in Austin, Texas, the formation consists of hard, white to yellow, unevenly bedded, nodular limestone which oxidizes to darker yellowish or pinkish shades because of its glauconite content. The Buda, named after a hamlet in Hays County, is the top formation of the Comanche series. At Austin, where its thickness is 45 feet, the Buda overlies the Del Rio clay and underlies the Eagle Ford shale.

Outcrop: The Buda limestone occurs at the same five localities listed for the Grayson marl: the Solitario (SW), Panther Mountain (SC), Packsaddle Mountain (SE), Gray Hill (SE), and east of the Old Stage Stand (NE). In each place the more resistant Buda caps the soft Grayson and thereby forms a cuesta or hogback. Precipitous Buda cliffs are common.

Because of the more rapid erosion of the underlying Grayson marl, the base of the Buda characteristically projects as overhanging ledges from which huge rectangular blocks, the result of almost right-angle jointing, become dislodged and come to rest on the more gently sloping Grayson surface. The gaping angular vacancies in the basal Buda plus corresponding cubical limestone blocks lying several feet below form a pattern that makes this contact identifiable even at great distances.

Thickness and lithology: The Buda limestone at Gray Hill is 69 feet thick. The section consists of hard, creamy white limestone that weathers to light gray. Irregular bedding accounts for the numerous nodules found as slope material, but a greater percentage of the float rock consists of angular fragments. Fresh outcrops of the limestone appear brecciated, and the disintegration of the brecciated rock masses presumably accounts for many of the angular pieces.

Thicker and somewhat massive beds, which exhibit the irregular bedding within themselves, occur in the lower part of the Buda section; but, in the upper portion, bed thickness decreases to 1.5–0.5 foot. Some marl is associated with the thinner and more unevenly bedded strata. The thicker beds contain little marl and are, according to Adkins (1933, p. 397), "a compact, fine grained 'porcellaneous' facies . . . a dense, light-colored limestone with pronounced conchoidal fracture." He further describes the more dense phases as "semi-lithographic".

Lechuguilla grows on the Buda limestone; and, where slopes are not excessively steep, a brush band follows the base. This band stands out rather conspicuously, for vegetation is generally scarce.

Fossils: Good identifiable fossils in the Buda are relatively rare, and few were obtained in place. Most specimens were collected on slopes and cannot be assigned to any definite vertical position. A tentative identification of the fossils found on the west flank of Gray Hill follows:

Corals—
  Cladophyllia?
  Solitary hexacoral
Echinoidea—
  Hemiaster calvini Clark
Pelecypoda—
  Pecten (*Neithea*) *subalpina* Böse

Pecten sp.
Internal mold of a pelecypod
Gryphaea mucronata Gabb
Exogyra clarki Shattuck
Gastropoda—
Turritella budaensis Shattuck
Pleurotomaria stantoni Shattuck
Several other unidentifiable gastropods
Cephalopoda—
Budaiceras sp.
Turrilites sp.
Fragment of an ammonite, probably 8–10 inches in diameter, with large straight ribs and prominent offset tubercles

STRATIGRAPHIC RELATIONS: The Grayson-Buda contact is sharp and apparently conformable, yet certain evidence suggests a hiatus at the top of the Grayson marl. Preserved in basal Buda limestone are possible internal molds of bore-holes up to 2 inches in diameter. The top of the Grayson appears to have been riddled with compound bore-holes before the deposition of the Buda, for the fucoidlike molds are crowded and intersecting. The Buda material that filled the tubes is clastic limestone with many shell fragments, some quite large. If these sedimentary features are true bore-holes, they are the horizontal variety, for none was found that projects more than a few inches down into the Grayson. That the casts are elliptical in cross section with the long axis parallel to the bedding suggests some settling after the tubes were made. Huge overturned blocks of fossiliferous basal Buda afford good exposures of the fucoidal bore-hole fillings.

There is no evidence for a disconformity at this contact in central Texas. If west Texas experienced a break in sedimentation, probably the hiatus represents only a submarine diastem.

A definite break occurs at the top of the Buda, for everywhere the contact with the overlying Boquillas flags is decidedly sharp. According to F. L. Whitney (personal communication): "So far as is really known, no species of the Comanche occurs in the Gulf." The abrupt lithological change at this contact plus the gentle undulations of the top of the Buda suggest a disconformity.

Gulf Series

Tentative correlation.—The following tentative and generalized regional correlations introduce the Gulf series stratigraphy of the Agua Fria quadrangle:

Agua Fria area	Central Texas
Aguja	Taylor
Upper Boquillas-Terlingua unit (= Terlingua ±)	Austin
Lower Boquillas-Terlingua unit (= Boquillas ±)	Eagle Ford

Because of gradational contacts, insufficiently detailed paleontological work in the Trans-Pecos region, and vague definitions of formational boundaries, the Gulf series of the area presents many stratigraphic problems. The most critical problem arises in the Boquillas-Terlingua sequence.

The Boquillas-Terlingua Problem.—Udden (1907b, p. 29–33) applied the name Boquillas flags to the basal formation of the Gulf series which, in the Chisos country, immediately overlies the Buda limestone and grades into the overlying Terlingua beds. The flaggy limestone strata he described are fossiliferous, thin bedded, sandy in places, have closely spaced joints, and are separated by delicate seams which may not appear on freshly exposed surfaces. A chalky texture characterizes the upper 100 feet of his Boquillas formation. The rocks are ordinarily cream grayish-white, but faint ferruginous red stains occur, and in some areas certain ledges are dark and almost black on fresh fractures. Udden gave a thickness of 585 feet to this western equivalent of the Eagle Ford shales. The type locality is in the vicinity of Boquillas [Hot Springs?] post office on Tornillo Creek in the Chisos Mountains quadrangle, Brewster County, Texas, about 40 miles southeast of the Agua Fria quadrangle.

Udden (1907b, p. 33–41) applied the name Terlingua beds to the yellowish-white, indurated, stratified chalk that gradually changes upward to an impure gray marl, which becomes less and less calcareous until it is a true clay. The uppermost clays contain some thin layers of concretionary limestone and calcareous sandstone. Both lower and upper Terlingua contacts are gradational. The formation rests on the Boquillas flags, and the Aguja sandstone overlies it. Udden correlated the Terlingua with the Austin chalk and Taylor marl of the central part of the State. He assigned a thick-

ness of 1250 feet to these beds and named them for exposures along Terlingua Creek in the Terlingua quadrangle, Brewster County, Texas.

Several new terms, though undefined at this point, are introduced in Figure 2. The problem, stated briefly, is: The Boquillas-Terlingua contact lies somewhere within the 300 feet of gradational strata between the *"Crioceras"* zone and the *Inoceramus undulato-plicatus* zone. The *"Crioceras"* zone is the uppermost clearly recognizable fossil zone with presently known unquestionable Eagle Ford fossils. The *Inoceramus undulato-plicatus* zone is the lowermost clearly recognizable fossil zone with presently known unquestionable Austin fossils.

Analysis of Udden's several definitions of the Boquillas and Terlingua led to the conclusion that the Fizzle Flat lentil of the Agua Fria area (Fig. 2) occupies a stratigraphic position fairly close to his intended Boquillas-Terlingua boundary. To avoid adding further to the confusion partly caused by the inexact nature of Udden's definitions, no attempt was made to show either the Boquillas formation or the Terlingua formation as such on the geologic map (Pl. 1). Instead, the Boquillas-Terlingua section was considered an entity, and a lower Boquillas-Terlingua unit (= Boquillas ±) and an upper Boquillas-Terlingua unit (= Terlingua ±) were mapped. In the 300 feet of strata between the *"Crioceras"* zone and the *Inoceramus undulato-plicatus* zone, the contact between the top of the *Austiniceras*? ledge and the base of the Fizzle Flat lentil (Fig. 2) is the most easily recognized one over the area as a whole. Consequently the base of the lentil was arbitrarily selected as the boundary between the lower Boquillas-Terlingua unit and the upper Boquillas-Terlingua unit.

Lower Boquillas-Terlingua unit.—Limestone flags of the lower Boquillas-Terlingua unit (= Udden's Boquillas ±) form the most widespread rock outcrops in the Agua Fria quadrangle. Exposures in the northeast portion of the area consist almost exclusively of this unit. Extensive outcrops also occur in the southern part of the area, where positive structures produce isolated patches of the flaggy strata surrounded by late Gulf and Tertiary beds.

THICKNESS AND LITHOLOGY: A continuous section of the lower Boquillas-Terlingua unit could not be found within the quadrangle. However, the sequence from the top of the Buda through the *"Crioceras"* zone is well exposed in the canyon walls of Terlingua Creek at the south boundary of the area. The only interruptions in this section are a dike 12 feet wide and a sill 50 feet thick. Vertical cliffs practically prohibited the collection of fossils from the lower 100 feet of this section.

The middle or critical portion of the Boquillas-Terlingua unit, from the *"Crioceras"* zone through the *Inoceramus undulato-plicatus* zone, is well exposed and quite accessible along the west bank of Terlingua Creek from the mouth of Alamo de Cesario Creek upstream for a distance of half a mile (Pl. 2, fig. 1). This locality is at the western extremity of Half Dome (SC).

The lower Boquillas-Terlingua unit can be conveniently divided into three lithologic units. These, with approximate thicknesses, are:

Upper shaly member	100 feet
Middle terraced member	205 feet
Lower nodular member	210 feet

LOWER NODULAR MEMBER: This member, slightly over 210 feet thick, contains hard, irregularly shaped calcareous concretions and nodules. The basal several feet are variable in color; shades of red, brown, yellow, and gray are common. There is also considerable lithological variation. A bed of brownish, indurated, limonitic sandstone, 2 to 3 inches thick, rests on the gently undulating surface of the Buda limestone. Above this, thin and irregularly bedded, impure, sandy limestone flags alternate with 1-inch seams of bentonite, silt, or fine-grained sandstone. These lower banded flags, 1–3 inches thick, appear laminated. Chert is found in some of the lower beds, and fat, disc-shaped calcareous concretions are locally abundant. Sandstone and especially silty shale increase in percentage upward from the basal heterogeneous beds so that the next 100 feet is predominantly rusty brown to dull-gray silty and sandy shale. The shale includes more resistant limestone beds, up to 4 inches thick, that occur at intervals of 4 or 5 feet. Most of the limestone beds contain small limonite nodules.

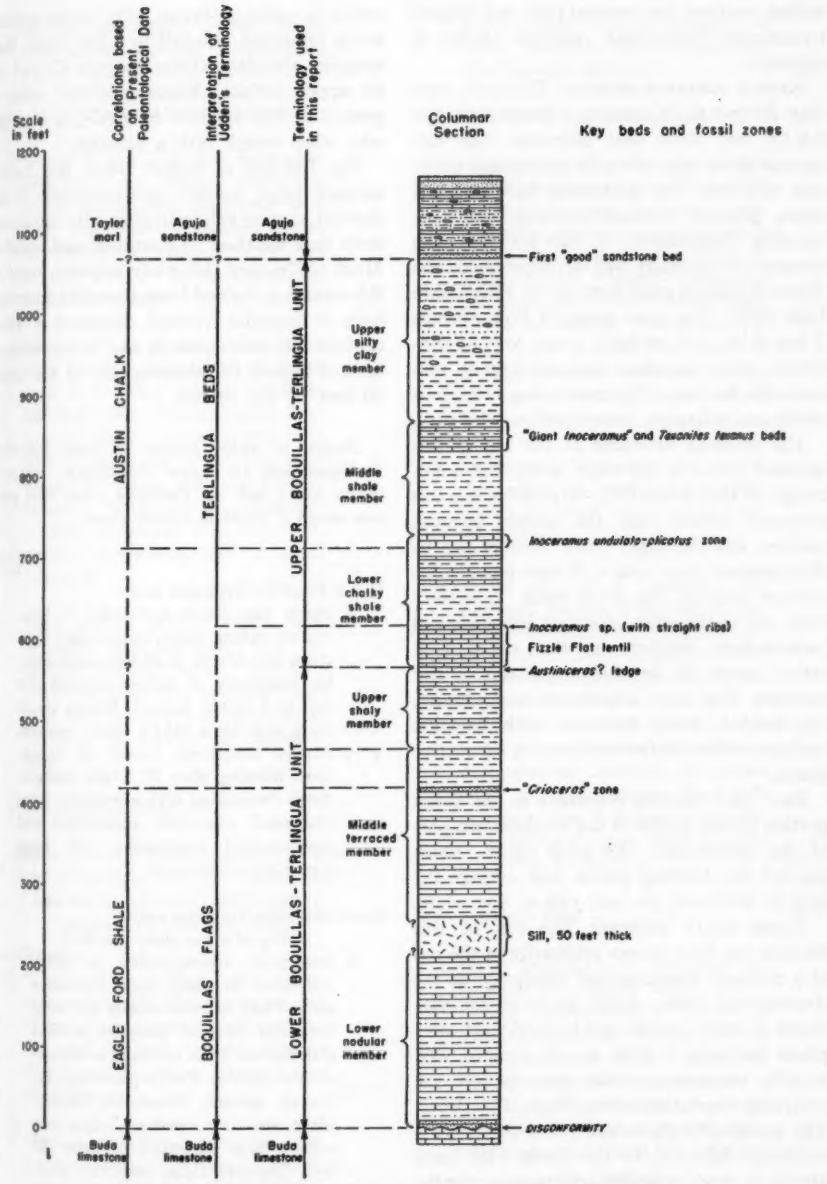


FIGURE 2.—CORRELATION OF GULF SERIES IN AGUA FRIA QUADRANGLE

In the upper 100 feet of the lower nodular member, medium dark-gray, silty to fine-grained sandy shale alternates with impure, cream-gray limestone beds that average a foot in thickness, weather to thin plates, and become more cream-colored upward. Nodules are present both in the shale and as more indurated portions of the limestone beds. This

section weathers into vertical cliffs and isolated topographic forms that resemble stacks or chimneys.

MIDDLE TERRACED MEMBER: This unit, more than 200 feet thick, consists of limestone ledges 0.5–1.5 feet thick that alternate with calcareous shale intervals with an average thickness of 3 feet. The alternating hard and soft strata produce erosional terraces, the outstanding characteristic of this member. The terraces are especially well developed along the Alpine-Terlingua road north of the Hale Cabin fault (NE). The more resistant beds average 1 foot thick, and are hard, cream to yellowish-brown, gritty limestone that weathers to thin shale-like laminae. The intervening calcareous shales are indurated, creamy yellow, and silty.

The resistant limestone at the top of this member forms a dip-slope along the south margin of Half Dome (SC). So prominent is this erosional terrace that the middle terraced member and the upper shaly member can be distinguished even with a 50-foot topographic contour interval. The 4-foot thick *"Crioceras"* zone, one of the most important lithologic and paleontologic markers in the entire Gulf series, occurs 50 feet below the top of this member. The zone consists of hard, brown, thin-bedded, sandy limestone with limonitic nodules, white calcite veins, and a distinctive fauna.

Rare color banding is present in the lower portion of this section in the southwestern part of the quadrangle. The color bands, which parallel the bedding planes and average 0.2 inch in thickness, are red, yellow, and white.

UPPER SHALY MEMBER: The top of this member has been chosen arbitrarily as the top of a resistant limestone bed referred to as the *Austiniceras?* ledge, which produces the dip-slopes of many cuestas and hogbacks. At most places the ledge is fairly heavily covered with scrubby vegetation, which contrasts with the overlying vegetation-barren Fizzle Flat lentil. The topography above and below the ledge is decidedly different. In the Fizzle Flat lentil above, a more rounded, curvaceous, gentle, low, and subdued topography prevails; the relief below is harsh and angular with plunge basins and canyons.

The *Austiniceras?* ledge is a hard, creamy yellow to yellowish-brown, silty to fine-grained sandy limestone, one-half to 1 foot thick, that contains abundant *Ostrea congesta* Conrad on its upper surface. Enough detrital silica is present in this stratum to give it a flint-like odor when struck with a hammer.

The 100 feet of section below the *Austiniceras?* ledge consists predominantly of indurated, creamy yellow to gray, silty calcareous shale that weathers to biscuit-shaped nodules. Much of the very thin platy material found in this section is derived from thin silty limestone beds of irregular vertical distribution. Lime content increases upward, and more resistant beds of impure limestone appear in the upper 40 feet of the section.

Section of upper portion of lower Boquillas-Terlingua unit (= upper Boquillas±) measured within half a mile up Terlingua Creek from point near mouth of Alamo de Cesario Creek.

	Thickness Feet
Upper Boquillas-Terlingua unit—	
6. Fizzle Flat lentil: Indurated to hard, creamy yellow, platy, impure silty limestone that breaks down into small angular fragments of almost uniform size (up to 2 inches square). Brown clastic dikes and white calcite dikes common. Almost completely barren of vegetation. Blinding glare in bright sunlight. Small *Inoceramus* with alternating large and small concentric undulations and medium-sized *Inoceramus* with large concentric undulations	43
Lower Boquillas-Terlingua unit—	
(Top of upper shaly member)	
5. Indurated, creamy-yellow to gray, laminated to platy, silty, calcareous shale. Platy material mostly thin silty limestone beds of irregular vertical distribution. Shale weathers to biscuit-shaped nodules. $CaCO_3$ percentage increases upward. Prominent, impure, platy, and silty limestone ledges containing large inocerami in upper 40 feet. Topmost thick, resistant, overhanging limestone bed (the *Austiniceras?* ledge) characterized by abundance of *Ostrea congesta* Conrad, a few cart-wheel ammonites, and large inocerami. Bed forms vegetation-	

covered dip-slopes; plunge basins and canyons develop in underlying strata..... 101.5

(Top of middle terraced member)

4. Similar to unit 2. A dirty brown bed with *Inoceramus labiatus?* Schlotheim and a medium-sized *Inoceramus* with large concentric undulations occurs 18½ feet above "*Crioceras*" zone. Top of this unit forms dip-slopes and erosional terraces..... 48.5

3. "*Crioceras*" zone: Alternating hard, dirty brown to gray-brown limestone beds of 4 inches average thickness and indurated, brownish-gray, laminated to platy, calcareous, silty shale with very thin and irregular lenses of impure limestone. *Baculites gracilis?* Shumard, "*Crioceras*" sp., *Scaphites?*, a small *Inoceramus* with large concentric undulations, and a small pelecypod..... 4

2. Hard, creamy yellow, 1-foot thick limestone beds alternate with indurated, creamy yellow, laminated calcareous shale that becomes somewhat silty upward and increases in thickness at expense of limestone beds..... 77.5

1. Northwest-southeast fault.

Section of lower Boquillas beginning on west bank of Terlingua Creek just outside south boundary of quadrangle and extending northward toward Hill 3450

Boquillas flags—

10. "*Crioceras*" zone: Hard, rusty brown to brown, evenly bedded and banded impure sandy limestone with numerous small limonitic nodules. Fossils: "*Crioceras,*" *Scaphites, Baculites gracilis?* Shumard..... 3 to 4

9. Hard, cream-colored limestone beds, 1± foot thick, alternating with shale beds 3 to 4 feet thick. Erosional terraces produce step-like slopes. Section is light-gray creamy yellow..... 134

8. Limestones and shales turned black by contact metamorphism..... 18

7. Badly altered, dark greenish-gray to black, analcime microsyenogabbro? sill of variable thickness..... 50±

(Top? of lower nodular member)

6. Alternating, dark-gray, silty to fine-grained sandy shales and 1-foot thick impure cream-gray limestone beds. Numerous calcareous nodules in shales and as more indurated portions of limestone beds. Chimney weathering. One large pseudoceratite found about middle of interval. Limestones become more cream-colored upward. At top, limestone and shale metamorphosed, banded, and weathered into thin plates..... 100±

5. Dark-gray to black shale zone at middle of which is a 1-foot bed of whitish, impure limestone that weathers into thin plates..... 10

4. Similar to unit 2. Sandstone and silty shale increase at expense of limestone beds so that section is predominantly rusty brown to dull-gray silty and sandy shales with prominent hard limestone beds, 3 to 4 inches thick, at intervals of 4 or 5 feet. Some limestone ledges are continuous and evenly bedded; others are lenticular; all contain small limonite nodules. Hard calcareous nodules and concretions common. Bentonitic beds, up to 2 inches thick, rare. Vertical cliff..... 95

3. Bentonite layer..... 0.3

2. Hard, grayish-brown, somewhat irregularly thin-bedded, flaggy, sandy, banded, impure limestone alternating with seams (average thickness, 1 inch) of bentonite, silt, or fine sandstone. Small, unidentified ammonite, 1+ inch in average diameter, resembles *Scaphites.* Brownish, indurated, limonitic sandstone in basal 2 or 3 inches. 6

———Disconformity———

Buda limestone—

1. Top of hard, white, porcellanous, irregularly bedded, nodular limestone with very gently undulating surface.

Certain special features are peculiar to the lower Boquillas-Terlingua unit at Red Bluff, where unquestionable Boquillas directly overlies an intrusive, and the flags are jet-black for a distance of 40 to 50 feet above the contact. Only slight metamorphic effects were observed near other intrusions, and it seems improbable that so thick a section of dark-colored limestones resulted solely from contact metamorphism. Udden (1907b, p. 31) says that in some areas certain ledges of the Boquillas are dark and almost black on fresh fractures. Perhaps the dark beds occur at Red Bluff by mere coincidence.

Close examination of the black flags reveals that mineralization has taken place high above the igneous-sedimentary contact, because the black rock has a higher density than ordinary Boquillas limestone. Certain strata contain peculiar, almost spherical epigenetic concretions that resemble algal structures and through which bedding planes extend. The sedimentary structures average 0.4 inch in diameter and consist of thin, siliceous shells, inside which the composition apparently approaches the normal Boquillas lithologic character. Slightly darker nuclei are present in some of the concretions, but the limestone outside the shells is black and more highly mineralized.

Although the supposed concretions are epigenetic, probably they were in existence before the Red Bluff intrusion. At the time the magma was injected, mineralization seems to have taken place in those portions of the limestone unprotected by the siliceous shells. Apparently the interiors of the concretions were largely shielded from such mineralization.

Many of the beds in this area have strong petroliferous and sulfurous odors. Perhaps much of the darker color is due to carbonaceous material. At the lower contact of the sill on the south flank of Red Bluff, much of the originally black material appears to have been driven off by heat.

These hard black limestones, like the normal Boquillas beds, weather to angular fragments. Some ledges are so brittle that they shatter easily when struck with a hammer.

Reddish patches are common in the Boquillas on the northeast flank of the Solitario (SW). Because these are near intrusive masses, it is assumed that they resulted from igneous activity and indicate mineralization.

FOSSILS: The lower Boquillas-Terlingua unit is generally quite fossiliferous; pelecypods and ammonites are most abundant. Poor preservation, due largely to fragility of the original shell material, frequently makes accurate determinations of species, and even genera, impossible. This applies particularly to several species of *Inoceramus*, which are present throughout the flaggy unit. The fauna is summarized from base to top.

Inoceramus labiatus Schlotheim is the most common fossil in the lower Boquillas-Terlingua and apparently ranges throughout the entire unit.

A small, unidentified ammonite, 1+ inch in average diameter, which resembles *Scaphites*, occurs 6 feet above the Buda contact.

A large pseudoceratite with only one small secondary saddle in the first lateral lobe was found about 50 feet below the top of the lower nodular member.

Twenty-five feet below the base of the "*Crioceras*" zone is a small, elliptical, ribbed *Inoceramus* (length, 1¼ inches; height, 1 inch). On this specimen, the concentric undulations are very fine and numerous, and the radiating ribs are comparatively coarse.

The hard, brown, sandy limestone beds which make up the 4-foot "*Crioceras*" zone contain several genera and species, and practically all specimens are filled with clear calcite crystals. These fossils, in order of decreasing abundance, are:

"*Crioceras*" sp.
Baculites gracilis Shumard
Scaphites sp.
Inoceramus labiatus Schlotheim
Inoceramus sp. (3+ inches in diameter)
Acanthoceras?

A *Prionotropis woolgari?* (Mantell), 9 inches in diameter, was found in the bed of a creek 2 miles west of Dewees Tank (NE). The stratigraphic position is near the top of the middle terraced member.

Several genera and species are found in the *Austiniceras?* ledge, a white, chalky limestone bed about 4 feet in average thickness. The ledge is named from one poorly preserved cart-wheel

ammonite which Adkins has seen and believes is *Austiniceras*, a Turonian form. The specimen, an internal mold, is a thin, evolute, sharp-keeled ammoniticone, 28 inches in diameter, with an imperfectly preserved, complicated suture. The form consists of four whorls; the maximum width of the living chamber is 2.5 inches, and its height is 1 foot. Gayle Scott (1926, p. 100) stated: "At the top [of the Eagle Ford], one finds . . . some carinate ammonites which, up to the present, have not been described. . . ." Adkins (1933, p. 431) wrote that the Boquillas flagstones ". . . contain near the top *Scaphites*, *Prionotropis*, a three-foot ammonite, *Inoceramus* cf. *labiatus* and other fossils. . . ." Perhaps Scott and Adkins referred to some such *Austiniceras?* form. If so, this suggests that the Boquillas-Terlingua contact is at the top of or somewhere above the *Austiniceras?* ledge.

Ostrea congesta (Conrad) Hall, although having a much greater vertical range, is characteristic of the *Austiniceras?* ledge. The upper surface of the bed is normally completely covered with these small oysters.

A poorly preserved ammonite, about 1 foot in diameter, is possibly a compressed *Prionotropis eaglensis* Adkins. Other smaller ammonites, 2 to 3 inches in diameter, were also noted in this ledge.

Several species of *Inoceramus* occur in the *Austiniceras?* ledge. One is *Inoceramus labiatus?* Schlotheim. Another larger form averages a foot across and has large concentric undulations on which fine rugae are superimposed. Possibly the ribbed species of *Inoceramus* collected by Stephenson from the top of the Fizzle Flat lentil occurs in this ledge.

A species of *Inoceramus*, which may be new, was found at the top of the *Austiniceras?* ledge. The internal molds range up to 1± foot across but are ordinarily about the size of a person's hand. The over-all shape is that of a fan, and the angle at the terminal beak is acute. The concentric undulations are diagnostic; most are highly raised and fairly sharp, but a few are low and well-rounded. Radiating from the beak toward the ventral margin of the shell for a little more than a third of the distance are several fairly well-developed ribs, which are neither as prominent nor as distinct as the undulations. This ribbed specimen is similar to but may not be the same as the species found by Stephenson at the top of the Fizzle Flat lentil.

Collected at random from Boquillas outcrops in the southwest part of the area were *Inoceramus labiatus* Schlotheim; a thin, discoidal ammonite, 2¼ inches in diameter, which may be *Placenticeras*; and a very small, evolute ammonite, half an inch in diameter, which consists of five whorls ornamented by numerous strong ribs.

STRATIGRAPHIC RELATIONS: Contact of the Boquillas with the underlying Buda limestone offers no problem, for a clear-cut break separates these two formations of different composition. The question always arises, however, as to whether this contact is disconformable. The gently undulating upper surface of the Buda, the sharp change in lithology, and the sandy basal few feet of the Boquillas suggest a hiatus. Perhaps the only erosion that took place at the close of Buda time was that caused by submarine currents, but there was certainly a break in sedimentation. Fossil evidence supports this conclusion, for Comanche and Gulf species are not found above and below the contact, respectively.

The Boquillas and the overlying Terlingua intergrade.

Upper Boquillas-Terlingua unit.—The upper Boquillas-Terlingua unit crops out extensively in the central portion of the south half of the mapped area. Owing to faults and talus slopes, a complete section suitable for measurement could not be found. The described section is compiled from measurements made from fossil zone to fossil zone at different localities.

The best and most accessible exposures of the lower part of the section, including the debated Boquillas-Terlingua contact, are in the Fizzle Flat fault block west, south, and southeast of Clanton ranch (C).

Fair exposures of the upper part of the upper Boquillas-Terlingua unit occur east of Agua Fria Mountain; talus is a problem, but the uppermost beds are not seriously interrupted by faults.

The map shows a complete upper Boquillas-Terlingua section southwest of north Pitahaya Hill (SC). This section is suitable for a detailed

study of the lower beds; but it seems that concealed faulting, perhaps with a northwest-southeast trend, has disturbed the Terlingua beds just below the Aguja. These unfavorable conditions discouraged the measurement of a section here.

THICKNESS AND LITHOLOGY: The upper Boquillas-Terlingua unit is a good example of vertical lithologic gradation. Yet sufficient difference permits the recognition of three lithostratigraphic units. The tops of two biostratigraphic zones provide convenient markers in the section and are the basis for the divisions shown in Figure 2.

LOWER CHALKY SHALE MEMBER: The transitional Fizzle Flat lentil might be considered a lithic average of the Boquillas and Terlingua formations; still it has a distinctive character that makes it a recognizable rock unit (Pl. 2, fig. 2). The lentil is yellowish, and its lithic composition is similar to that of the underlying Boquillas flags. Yet laminae, biscuit-shaped nodular weathering, gray color on fresh surfaces, scarcity of fossils, lack of vegetation, and gentle slopes suggest the overlying Terlingua shale. The relatively sharp contact of the Fizzle Flat lentil with the underlying *Austiniceras?* ledge and the several common properties of the lentil and the Terlingua favor the inclusion of the 50-foot lentil as the base of the upper Boquillas-Terlingua unit. The upper contact of the lentil with the overlying gray shale is gradational within a few feet. This contact is clearly exposed just southwest of the Cheosa Waterhole fault scarp on the road leading westward toward Cheosa Waterhole (C) from the Alpine and Terlingua road. Specimens of Stephenson's *Inoceramus* sp. (with straight radiating ribs) were collected from the top of the lentil at this locality.

Approximately 90 feet of gray, relatively unfossiliferous, calcareous shale lies between the Fizzle Flat lentil and the *Inoceramus undulato-plicatus* zone. This shale weathers to biscuit-shaped nodules on steep slopes.

Thin beds of hard, white, chalky limestone appear in the gray shale section some 60 feet above the top of the lentil, and they become more abundant upward toward the *Inoceramus undulato-plicatus* zone. These chalk beds contain few fossils, are nodular, highly jointed, and average 6 inches in thickness. The alternating gray and white beds characterize the 30 feet of section below the *Inoceramus undulato-plicatus* zone.

The *Inoceramus undulato-plicatus* zone was chosen as the top of the lower chalky shale member, because it is everywhere a recognizable lithologic and paleontologic marker. In places the zone attains a thickness of 12 feet. It consists of very fossiliferous, hard, light creamy yellow-gray, unevenly bedded, nodular, silty limestone ledges and silty shale. So consistently do the ledges hold up dip-slopes that the resulting cuestas and hogbacks are easily recognized even on small-scale aerial photographs.

The total thickness of the lower chalky shale member is about 150 feet.

Section of the lower portion of the upper Boquillas-Terlingua unit measured in the Blue Hills area 1 mile south-southwest of Clanton ranch

	Thickness Feet
Upper Boquillas-Terlingua unit—	
10. *Inoceramus undulato-plicatus* zone: Over-all color is light creamy yellow-gray. Basal 1 foot is a hard limestone bed; next is a 1-foot section of irregularly bedded, nodular, silty limestone; then 4 feet of silty shales; and the up-	

PLATE 2.—BOQUILLAS-TERLINGUA SEQUENCE

FIGURE 1. LOWER BOQUILLAS-TERLINGUA UNIT

Middle terraced member in foreground, upper shaly member in cliff in background. On Terlingua Creek upstream from mouth of Alamo de Cesario Creek. (Photograph by R. B. Davis.)

FIGURE 2. FIFTY-FOOT FIZZLE FLAT LENTIL, PRACTICALLY BARREN OF VEGETATION

Flat-lying Boquillas flags in Cheosa Waterhole fault scarp in background. Looking eastward toward Nine Point Mesa on horizon. (Photograph by R. B. Davis.)

FIGURE 3. WEST FLANK OF PANTHER MOUNTAIN, A TRAP-DOOR DOME

Lighter-colored Boquillas-Terlingua beds dragged up along darker vertical wall of rhyolitic intrusion. Roof rock on skyline is upper Devils River limestone. (Photograph by R. B. Davis.)

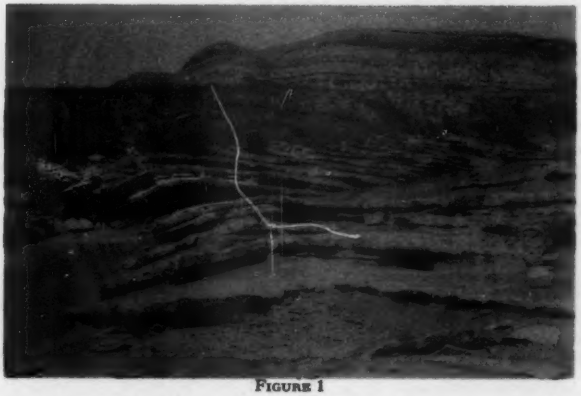


FIGURE 1

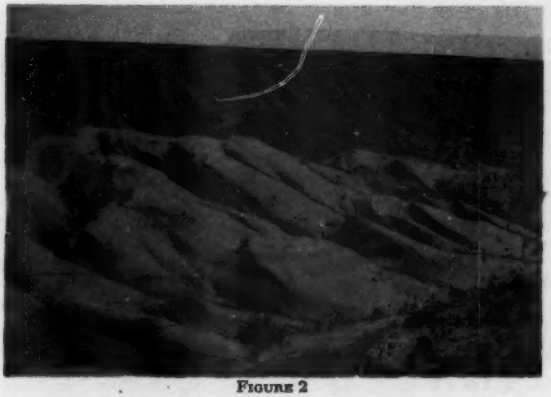


FIGURE 2

FIGURE 3

BOQUILLAS — TERLINGUA SEQUENCE

FIGURE 1

FIGURE 2

FIGURE 3

TUFFS AND TOPOGRAPHIC FORMS

permost foot is a nodular, impure, silty limestone with numerous *Inoceramus undulato-plicatus* Roemer. These limestone ledges produce dip-slopes characterized by creosote bush vegetation..... 7

9. Gray shale section: at some horizons calcareous enough and sufficiently indurated to form zones of large, jointed, nodular, fossiliferous, concretionary masses or individual thin beds of shaly, chalky limestone. Interval becomes sandy (fine-grained) and yellowish in uppermost 5 feet..... 27

8. Hard, glaring white limestone bed; weathers to odd-shaped, nodular concretionary masses. Highly complex pattern of closely spaced joints; ledge disintegrates into small angular fragments. Some limonitic stain, especially along joints..... 1

7. Shale similar to unit 5..... 6.5

6. Bed of hard to indurated, glaring white, chalky limestone. Very intricately jointed..... 0.75

5. Indurated to friable, gray, laminated, calcareous shale. Very thin bentonitic seam about 10 feet from top of interval. Uppermost 5 feet somewhat silty and has a slightly yellowish tinge. Almost vertical brown clastic dikes and white calcite dikes. Fresh shales are dark gray to black and practically nonfossiliferous..... 59

4. Fizzle Flat lentil (= "barren" or "transition" zone): Indurated to friable, gray to creamy yellow, laminated to platy, silty, and chalky shale with occasional seams of bentonite less than one-fourth inch thick. More silty and sandy in lower 10 feet and increasingly chalky upward. Thin chalky plates crackle and crunch when walked upon. Everywhere barren of vegetation and typically cream-yellow (gray in unweathered exposures). Some zones exhibit gray biscuit weathering similar to that of typical Terlingua. Brown clastic dikes common. A peculiar *Inoceramus* (species with well-developed, straight, radiating ribs collected by Stephenson) abundant in uppermost part of section. Similar forms with less well-developed ribs occur throughout the lentil. One hard, yellow-brown, nodular limestone with *Inoceramus* cf. *labiatus* Schlotheim at top..... 50

Lower Boquillas-Terlingua unit—

3. Hard, light-brownish, thin, and unevenly bedded, somewhat nodular, sandy limestone bed. *Ostrea congesta* Conrad abundant and a few poorly preserved inocerami..... 0.25

2. *Austiniceras?* ledge: Whitish to brownish-gray silty shales and thin, irregularly bedded, nodular, impure silty limestone ledges. Same fossils as unit 1, plus a thin sharp-keeled, cart-wheel ammonite 28 inches in diameter (*Austiniceras?*) and a ribbed *Inoceramus* similar to that at top of Fizzle Flat lentil..... 4

1. Top of hard, most resistant, yellowish-brown to white, silty limestone ledge, about 1 foot thick, near top (?) of Boquillas. All fossils poorly preserved; *Ostrea congesta* Conrad attached to a large *Inoceramus* with concentric undulations and fine rugae, an ammonite 2 to 3 inches in diameter, *Inoceramus labiatus?* Schlotheim, and part of an ammonite 9 to 10 inches in diameter.

PLATE 3.—TUFFS AND TOPOGRAPHIC FORMS

FIGURE 1. WHALEBACK HILL IN TUFF OF NORTHWESTERN PART OF QUADRANGLE
(Photograph by R. B. Davis)

FIGURE 2. GROTESQUE EFFECTS IN DEVILS GRAVEYARD PRODUCED BY COMBINATIONS OF RESISTANT AND WEAK BEDS IN TUFF

FIGURE 3. UNCONFORMITY WITHIN BUCK HILL VOLCANIC SERIES AT WHISTLER SQUAT
Several dark conglomerate lenses occur just above break separating calcareous tuff below from more calcareous tuff above.

MIDDLE SHALE MEMBER: The 90-foot interval above the *Inoceramus undulato-plicatus* zone consists essentially of loose to friable, gray, laminated calcareous shale that weathers to biscuit-shaped nodules. Portions of the shale section are silty and weather to a dingy cream-gray; *Ostrea* fragments and *Inoceramus* prisms are randomly distributed. Thin seams of light-brown, fine-grained sandstone occur at irregular and widely spaced intervals. Disseminated gypsum and a small percentage of fine-grained sand appear in the shale upward from 50 to 65 feet above the *Inoceramus undulato-plicatus* zone, respectively. Those parts of the section with a sandy content weather to a creamy yellow at most places.

Some thin, brown sandstone beds about 75 feet above the *Inoceramus undulato-plicatus* zone are, more correctly, a sandy agglomerate of *Inoceramus* prisms. This larger sized bioclastic material suggests more turbulent waters during the time the beds were deposited.

A 10- to 15-foot sequence of gray calcareous shale, which includes a few thin beds of hard, pure-white, highly jointed, nodular and concretionary chalky limestone, is present just below the giant *Inoceramus* beds. Large *Texanites* are common in the thin chalky ledges. This lithologic sequence is similar to that just below the *Inoceramus undulato-plicatus* zone.

The giant *Inoceramus* beds, a less obvious stratigraphic marker than the *Inoceramus undulato-plicatus* zone, occur about 100 feet above the latter and are named for an extremely large species of *Inoceramus* that is abundant in them. Most of the fossil remains are internal molds up to 3 feet across, but very thick prisms and massive hinge-line structures are also found. The giant *Inoceramus* section is variable in thickness, but 35 feet is probably an average figure. Lithologically these chalky fossil beds do not everywhere contrast sufficiently with the enclosing gray shale to permit reliable identification. They do not consistently form persistent dip-slopes as do the *Inoceramus undulato-plicatus* zone and the *Austiniceras?* ledge. Where the giant *Inoceramus* beds crop out in a stream valley in which weatherng products are kept scoured off, the limestones are easily recognized as thick white ledges. On hill slopes, the chalky beds are easily covered over and discolored by slope wash so that they blend with the gray shales.

Good outcrops of the prolifically fossiliferous giant *Inoceramus* and *Texanites texanus* beds are found on Terlingua Creek three-quarters of a mile downstream from the mouth of Alamo de Cesario Creek (SC); a mile south of and also a mile east-southeast of Whistler Squat (SW); and 2 miles east-southeast of Clanton ranch (C).

A generalized sequence of the beds just under the giant *Inoceramus* beds 1 mile east-southeast of Whistler Squat is:

6. 1½-feet of creamy yellow-gray, impure nodular limestone with huge inocerami, *Ostrea congesta* Conrad, *Texanites*, etc.
5. 2± inches of purplish *Gryphaea* agglomerate.
4. 2 feet of impure silty clays.
3. Few inches of yellowish gray, thin-bedded, calcareous sands.
2. Yellow to gray clay-shales.
1. 10- to 15-foot sequence of widely spaced, thin, white, jointed, nodular chalky limestone ledges with *Texanites*, in a gray calcareous shale.

The giant *Inoceramus* beds appear to vary in hardness from place to place, perhaps due to a variation in $CaCO_3$ content. The beds ordinarily occur as indurated to hard, cream-colored, fairly thick and unevenly bedded, highly fossiliferous, nodular, chalky limestone ledges set in gray, calcareous, silty shales. This section of alternating shales and limestones is 35± feet thick, and the topmost ledge especially is prolific with *Texanites texanus* (Roemer) Spath.

The total thickness of the middle shale member is approximately 135 feet.

Partial section of middle? Terlingua beds measured on west flank of north Pitahaya Hill

	Thickness Feet
Terlingua beds—	
8. Soft and loose to friable, light-gray, laminated calcareous shale with disseminated gypsum. Ten feet above base of unit is a thin zone from which numerous fragments of a large *Inoceramus* weather to form slope material. Shells of *Ostrea congesta* Conrad attached to	

these *Inoceramus* prisms. Shaly material weathers to creamy yellow where exposed as a hill top..... 80+

7. Similar to unit 5..... 1

6. Similar to unit 4 plus some limonitic stains..... 8.5

5. Hard, light-brown sandstone layer with fragmentary inocerami. Weathers easily because of nodular character and contributes much slope material..... 1.5

4. Loose to friable, light-gray to gray, laminated, calcareous shale. Fragments of *Inoceramus* and *Ostrea?* shells. Occasional thin seam of light-brown, fine-grained sandstone in lower portion of interval with small amount of bentonite 37

3. Indurated, creamy brown, nodular, impure silty and sandy limestone with fragments of large *Inoceramus* shells.... 1.5

2. Silty gray shale weathers to a dingy cream-gray. *Inoceramus* fragments... .. 4

1. Top of *Inoceramus undulato-plicatus* zone.

Partial middle Terlingua section measured on west bank of Terlingua Creek three-quarters of a mile downstream from mouth of Alamo de Cesario Creek

	Thickness Feet
Terlingua beds—	
3. *Texanites texanus* bed: Indurated to hard, creamy yellow, irregularly bedded and nodular impure marly limestone with giant inocerami.....	3.5
2. Friable to indurated, gray, laminated, calcareous silty shale—weathers to biscuit-shaped nodules and yellowish color..	25
1. Top of resistant, white limestone bed with petroliferous odor and many giant inocerami.	

Partial middle? Terlingua section measured on west bank of Terlingua Creek east of Agua Fria Mountain

	Thickness Feet
Terlingua beds—	
3. Indurated, creamy yellow, irregularly bedded, nodular impure limestone and marl with giant inocerami.....	6
2. Loose to friable, gray, laminated calcareous shale.....	98
1. Top of *Inoceramus undulato-plicatus* zone; somewhat sandy.	

UPPER SILTY CLAY MEMBER: The thickness of 200 feet assigned to this member, composed of soft and easily weathered rocks, is an estimate. Gravel-covered slopes, concealed faulting, steep and non-uniform dips, and lack of good bedding made accurate measurement difficult to impossible.

The upper silty clay member grades into the overlying Aguja sandstone. For mapping purposes, the first true sandstone bed was arbitrarily chosen as the base of the Aguja. By definition, then, this member, in the Agua Fria quadrangle, consists of those beds lying between the base of the lowermost hard, rusty brown sandstone bed of the Aguja formation and the top of the *Texanites texanus* bed some 200 feet below.

The basal beds of this member are typical gray Terlingua shale. A gradation upward results in a rusty brown silty marl. Gypsum, already noted in the middle member, steadily increases in percentage from bottom to top so that large plates, which glitter in the sunlight, occur in the higher beds.

Silty clay-shale occurs 50 to 60 feet above the middle member, and the section becomes still more silty upward. Originally grayish, the clay-shale weathers to a dirty yellow.

Slightly sandy, yellowish, friable to loose clay and shale with numerous *Gryphaea wratheri* Stephenson and very thick prisms and hinge-line structures of a large *Inoceramus* occur fairly high in the upper member.

The thickness of the youngest Terlingua section or transitional beds varies with locality because of gradation. In places the Terlingua is loose, light-brown, massively bedded, bentonitic, fine-grained sandy or silty clay with a carpet walk: The swelling of the bentonitic clays produces a cushiony effect, which makes one feel that he is walking on a plush carpet.

The transitional beds are highly gypsiferous, and large plates of clear gypsum sparkle like jewels on some hillsides. A white, crusty efflor-

escence appears in many places on the surfaces of this dull yellow-gray silty clay. Many large, isolated *Inoceramus* shells are found in the transitional beds. Large white calcareous concretions and septaria, many of which appear to be cracked chalky limestone nodules, are outstanding features; most are scattered throughout the sandy clay section, but some occur in definite horizons.

The upper silty clay member of the upper Boquillas-Terlingua unit is exposed northeast of Agua Fria Mountain, north of north Pitahaya Hill (SE), and half a mile east of Mesquite Tank (SW). An estimated 200 feet of the gray marly shale and clay lies above the *Texanites texanus* beds east of Agua Fria Mountain, and the gradation into the overlying Aguja is visible. The best exposure of an almost complete upper section lies half a mile east of Mesquite Tank, but the locality is rather inaccessible, and the slopes are almost vertical; so a detailed measurement is practically impossible. Approximately 200 feet of faintly greenish yellow-brown silty clay, overlain by 20 to 40 feet of undisputed Aguja sandstone, with a wavy unconformity at its top, plus 15 to 20 feet of basal Tertiary conglomerate are excellently exposed. A good and easily accessible locality of the Terlingua-Aguja transition zone is 1 mile northeast of Clanton ranch.

Section of upper Terlingua beds beginning at top of Inoceramus undulato-plicatus zone southeast of Hill 3494 (SC) and working northeastward toward inlier of Aguja

	Thickness *Feet*
Aguja? sandstone—	
9. Hard, rusty brown bed of fine-grained sandstone	1
Terlingua beds—	
8. Transition zone with carpet walk. Loose, light-brown, massively bedded, highly gypsiferous, bentonitic, fine-grained sandy or silty clay. White calcareous septaria	52
7. Typical gray shales in basal 50 feet. White calcareous concretions appear 55 feet above base of unit. Section weathers yellowish upward. Large plates of gypsum in upper 50 feet. Base of 20-foot zone of scattered, white, jointed, chalky concretions occurs 50 feet below top of unit. Thirty feet below top, thin beds of fine-grained, yellowish-brown to light brown sandstone appear. Just above lowermost thin sandstone bed is a 2-inch bed of white, highly jointed, chalky limestone	139
6. Covered and thickness questionable (measured on basis of projected dip)	157
5. Top of *Texanites texanus* bed.	
(Section broken by faulting)	
4. Giant *Inoceramus* beds: At base is a 1-foot, cream-colored, nodular, chalky ledge; then 5 feet of silty shale; next a resistant, prominent, 1-foot thick nodular limestone ledge; 5 feet more of shale; and at the top another 1-foot, nodular, chalky ledge. (Probably an incomplete section of these beds.)	13
3. Friable to loose, dark-gray to black, finely laminated calcareous shale cut by brown clastic dikes; gypsum present but not abundant. Slopes weather to a soft, loose, gray material, are littered with *Inoceramus* prisms, *Ostrea* fragments, and small pieces of brown, thin-bedded sandstone and sandy agglomerate of individual *Inoceramus* prisms. Fine-grained sand content appears about 30 feet above base of unit and color of section upward is creamy yellow (probably due mostly to weathering). A more calcareous and better indurated 1-foot bed of shale stands out on face of cliff 38 feet above base	72
2. Covered	35
1. Top of *Inoceramus undulato-plicatus* zone.	

A striking characteristic of the upper Boquillas-Terlingua unit is its soft gray color, but local shades of light brown and yellow result from weathering. This is exemplified by the yellowish-brown tops of the gray cliffs along Terlingua Creek where the gray-brown color contact crosses bedding planes of the dipping strata.

There is believed to be but one *Inoceramus undulato-plicatus* zone in the Agua Fria quadrangle, as revealed by outcrops along the 2-mile stretch of Terlingua Creek just west of Clanton ranch and at other localities, but the zone has been repeated by faulting in the section exposed along Cat Draw (C and WC) and at several other places.

Thin, persistent, almost vertical clastic dikes of fine-grained brown sandstone—and also white calcite dikes—are common, especially in the lower part of the unit. An impression of an *Inoceramus* was found in one of the clastic dikes in the Blue Hills area 1 mile south-southwest of Clanton ranch.

FOSSILS: The paleontology of the upper Boquillas-Terlingua unit is summarized, tentatively, as follows (thicknesses in feet shown in parentheses):

Upper silty clay member (200?)—
"Transitional beds" (50?)—
Inoceramus sp.
Silty clay (150?)—
Gryphaea wratheri Stephenson
Gryphaea aucella? Roemer
Inoceramus sp. (large, with thick prisms)
Ostrea congesta Conrad
Thin pelecypod? shell fragment with numerous short spines (*Spondylus?*)
Middle shale member (135)—
Texanites texanus bed and giant *Inoceramus* beds (35±)—
Hemiaster texanus Roemer
A brachiopod
Inoceramus sp. (giant, up to 3 feet across)
Inoceramus sp.
Gryphaea wratheri Stephenson
Gryphaea sp.
Ostrea congesta Conrad
Ostrea sp.
Spondylus guadalupae? Roemer
Duronia terlinguae Adkins
Pelecypod? shell fragment with small spines
Eutrephoceras sp.
Texanites texanus (Roemer) Spath
Texanites sp. (thin)
Placenticeras sp.
Parapachydiscus?
"Hamites"
Other unidentified ammonites
Small cephalopod? with a rostrate venter
Onychodus? teeth
White chalky ledges (15±)—
Texanites texanus (Roemer) Spath
Gray shale (85)—
Inoceramus sp. (large shells, thick prisms)
Ostrea sp.
Lower chalky shale member (150)—
Inoceramus undulato-plicatus zone (10±)—
Inoceramus undulato-plicatus Roemer
Inoceramus sp. (thin shell)
Gryphaea wratheri Stephenson
Texanites cf. *texanus* (Roemer) Spath
Texanites sp. (thin)
Peroniceras? (or an evolute *Texanites*)
Gauthiericeras? (or *Texanites?*)
Texanites? (18 inches in diameter, 3¾ inches thick)
Texanites? (1+ foot across; 5 prominent nodes on each rib)
Placenticeras?
Onychodus? teeth
White chalky ledges (30)—
Inoceramus cf. *subquadratus* Schlüter
Inoceramus sp.
Anisomyon patelliformis Meek and Hayden
Texanites sp.
Gray shale (60)—
Inoceramus sp.
Fizzle Flat lentil (50)—
Inoceramus sp. (with straight ribs)
Inoceramus sp. (with strong undulations)
Inoceramus cf. *labiatus* Schlotheim
Ostrea sp.
Prionotropis? (small)
Other small ammonites
Isopods??
Shark teeth
Bone fragment

Stephenson (1948) said of the *Inoceramus* sp. (with straight ribs):

"In the upper part of the transition zone [Fizzle Flat lentil] is a distinctive species of *Inoceramus* (with radiating costae), the significance of which as an index fossil has not yet been determined. This appears to be the species that Adkins compared to *Inoceramus digitatus* Sowerby, and he considered it to be an Austin species."

On the basis of this statement, the writer is inclined to call the Fizzle Flat lentil, provisionally, basal Terlingua, although certain species of *Inoceramus* and ammonites found in the lentil strongly suggest similar forms found lower in the Boquillas section. Perhaps a more thorough paleontological study of the lentil will reveal an intermingling of both Austin and Eagle Ford forms within it. The Fizzle

Flat lentil in the Agua Fria quadrangle is a distinct lithologic unit that could serve as a key unit to which later-discovered paleontologic zones can be referred.

STRATIGRAPHIC RELATIONS: Both upper and lower contacts of Udden's Terlingua formation are gradational, and the transition upward into the Aguja is very gradual. Ross A. Maxwell, working in the Big Bend National Park, finds many *Exogyra ponderosa* Roemer about 100 feet below the top of his Terlingua formation. F. L. Whitney (personal communication) stated: "*Exogyra ponderosa* Roemer occurs on Little Walnut Creek near Sprinkle a few miles from Austin, probably 15 to 20 feet below *Exogyra tigrina* and *Exogyra laeviuscula* and, therefore, quite a distance below the Austin-Taylor contact." *Exogyra ponderosa* has not been found in the Agua Fria area. Because this fossil is found below the Austin-Taylor contact in central Texas, its absence here suggests the possibility that the uppermost Terlingua beds in this area are Austin in age and that none of them are young enough to be called Taylor.

Aguja formation.—Adkins (1933, p. 505, 506) wrote:

> "When in 1907 Dr. Udden described his 'Rattlesnake' formation, the name had already been used for a formation in the Oregon Pliocene. Accordingly the name Aguja is here substituted for Udden's name. The type locality is Sierra Aguja (Needle Peak), in the flat in front of the Santa Helena fault scarp, 6 miles south of Terlingua, Brewster County, Texas. The slopes and surrounding flats contain a practically complete section of the beds, overlain by the Tornillo clay, and situated close to Udden's original type locality. . . .Three widespread types of sediments compose the Aguja: (1) rather coarse grained fossiliferous sandstones, weathering to dark brown, tan, yellowish-brown, and blue-gray shades; (2) lustrous to dull black, non-marine, carbonaceous, lignite-bearing shales . . . ; (3) massive shelly clays, somewhat like those in the Taylor but generally weathering more yellowish-brown, and generally more sandy or silty."

The lower part of the Aguja is of Taylor age, and Adkins assigned the upper part to the Navarro. The Aguja is the youngest Cretaceous formation in the Agua Fria area.

OUTCROP: The easily eroded Aguja generally crops out in the Agua Fria quadrangle only where conditions for preservation are favorable—down-dropped fault blocks and places where the soft Aguja is protected by an igneous cap, the basal Tertiary conglomerate, talus, or a gravel cover.

Isolated Aguja outcrops are found southwest, west, and north of Agua Fria Mountain; south of Half Dome; south of the Fizzle Flat fault scarp; a mile east of Clanton ranch; Pitahaya Hills; and the extreme southeast corner of the quadrangle. All these exposures except the one near Clanton ranch are confined to the southern third of the area.

THICKNESS AND LITHOLOGY: The occurrence of the Aguja in relatively small isolated patches plus a major unconformity that affects principally the Terlingua and Aguja formations eliminate the possibility of a complete Aguja section in the Agua Fria quadrangle.

The outcrops of Aguja immediately south of Half Dome consist primarily of sandstone and shale. The shale is light to dark gray or almost black and blackish-red. Lignite is present, and lignitic shales are fairly abundant. One light-gray sandstone bed is so loosely cemented that it weathers to piles of sand that have been shaped into dune-like forms by the wind. This sandstone bed contains many fossils, oysters and shark teeth the most abundant. Also typical are calcareous concretions, ironstone concretions and septaria with aragonite fillings, fucoids, and cone-in-cone structures. Common minerals are gypsum and barite. The over-all color of these exposures is rusty brown. The Aguja fault blocks are synclinal with steep dips, so that much section can be seen in a short horizontal distance.

The most accessible Aguja occurs in a fault block east of the Clanton ranch, where the formation is exposed for an east-west distance of almost 2 miles. The Terlingua-Aguja transitional zone, in which the gray silty to sandy clay of the Terlingua grades upward into yellowish-gray, gray, and brown Aguja sandstone, is well exposed 1 mile northeast of the ranch house. The Aguja consists mostly of brownish sandstone and sandy clay of such heterogeneous character that the weathered outcrop resembles a mine dump. Both high-

and low-spired gastropods and oyster shell fragments were found north of the road 2 miles east of the ranch, and practically all the sedimentary structures of the area south of Half Dome were found at the Clanton ranch locality.

The lower Aguja sandstone in the extreme southeast corner of the quadrangle is so well cemented with calcareous and ferruginous cements that it holds up a prominent north-northwest trending fault scarp. About halfway up the scarp face is a prolific fossil zone. At another near-by locality of a stratigraphically higher position, numerous oysters weather from a ferruginous sandstone. These can be found on the dip-slope inclined eastwardly toward Hill 4142 at the intersection of the fence line and a north-south draw. South of Hill 4142, possibly in the middle Aguja beds, large fragments of dinosaur bones and armor plates, ironstone beds and concretions, cone-in-cone structures, calcareous septaria, ripple marks, and much gypsum were found in the yellowish-brown sandy clay, thin-bedded and laminated sandstone, and massive beds of friable, light-yellow sand. No lignitic shale was observed in this area, which is indirect evidence for assigning these outcrops to the lower Aguja.

The uppermost Terlingua, the Terlingua-Aguja transition zone, and the basal Aguja are exposed on the north slopes of north Pitahaya Hill. This combined section is buff or yellowish-brown, poorly consolidated, gypsum is abundant, and numerous calcareous septaria occur just below the igneous cap. Massively bedded silty clay or marl, which grades from yellowish brown-gray at base to rusty yellowish-brown at top, makes up almost the entire section at the south end of the same hill. Slope materials are loose to friable due to the bentonite, sand, and silt content, and a cushiony or carpet walk results. Many large slabs of clear gypsum are present near the base of the hill. Higher in the section thin beds of yellow, laminated to platy fine-grained sandstone, calcareous septaria with brown calcite and aragonite vein fillings, and cone-in-cone structures appear. There is an occasional massive bed of loose to friable light-yellow sand, and few layers of rusty brown sandstone occur in the massive clays near the top of the hill. One small gastropod was found about halfway up the hill.

Northwest of Packsaddle Mountain, the normal gray Terlingua clay grades upward into low, whaleback-shaped hills of brownish Aguja. Walking or driving an automobile on the flat just north of these hills is difficult, for it is underlain by the soft, bentonitic cushiony Terlingua-Aguja transition zone. Where exposures are best, the upper gray Terlingua grades into light-brown Terlingua-Aguja and this into brown basal Aguja, from which fragments of hematite weather.

The Aguja is exposed over a large area north of Agua Fria Mountain. The Terlingua-Aguja contact extending from Agua Fria Mountain to Paint Mountain can be located fairly closely on aerial photographs because of the different topographic patterns that develop in the two formations. Although too small to be shown on the map, several outcrops of disturbed Aguja beds occur along the Tascotal Mesa fault west of Paint Mountain.

Lignitic shale of the Aguja crops out at Agua Fria Spring. These beds are part of a very narrow Aguja fault block which fringes Agua Fria Mountain to the northwest, west, and southwest. Undoubtedly the high permeability of the lower Aguja sandstone partially accounts for the perennial spring.

Aguja fragments and sedimentary structures in the dams of earthen stock tanks indicate that much of the alluvium-covered flat between south Pitahaya Hill and Camels Hump is underlain by Aguja. Aguja beds concealed by a thin alluvium sheet are probably continuous from south Pitahaya Hill to the southeast corner of the quadrangle.

In most places, the lower Aguja section consists of loosely cemented, light-colored sandstone. Although rare in the Agua Fria area, cannonball concretions are abundant in the lower sandstones farther south.

Partial section of lower Aguja measured on west side of hill 1¼ miles southwest of Clanton ranch

Aguja sandstone—

12. Top of hill.

11. Friable to indurated, yellowish-gray to dark-gray, fine-grained sandstone.

	Thickness Feet
Bedding consists of poorly developed irregular plates within a massive bed. A few poorly preserved ripple marks	3.5
10. Loose, whitish-gray, massively bedded, fine-grained sand	10
9. Loose to friable, brownish-gray, massively bedded, somewhat bentonitic silty clays and marls with occasional small white limy concretions and few very thin rusty brown sandstone layers	27
8. Hard to indurated, light-brown, fine-grained sandstone. Weathers to plates. Ripple mark impressions preserved in base	2
7. Large, hard, yellowish- to light-brown, flattened, somewhat connected, lenticular limestone concretions enclosed in fine-grained sandstone matrix	0.5 to 1
6. Thin bed of indurated, tan to light rusty brown, fine-grained sandstone. Breaks down to fragments of pebble and cobble size	0.5
5. Loose, dull olive-green to light-brown, massively bedded, silty clay-shale with 6-inch parting of rusty brown sandstone 15 feet above base. White chalky concretions scattered throughout bentonitic section. Large gypsum plates as float on slopes	42
4. Hard, rusty brown bed of highly fractured fine-grained sandstone with broad, symmetrical ripple marks (3 inches from crest to crest)	0.5
3. Loose, rusty brown, massively bedded, gypsiferous and bentonitic silty clay	14
2. Hard, rusty brown bed of fine-grained sandstone (= lowest good sandstone)	1
Total lower Aguja present	101.5

Terlingua? beds—

1. Transitional zone: Loose, light-brown, massively bedded, highly gypsiferous, bentonitic, fine-grained sandy to silty clay with carpet walk. White calcareous septaria.... 52

At two small outcrops of Aguja, sandstone has been altered to quartzite by contact metamorphism. One locality is Hill 3473 (SE), and the other is on the downthrown side of Cheno Waterhole fault just west of its intersection with latitude 29°35′ N. The latter is a small outlier where an uncovered decomposed sill (?), which exhibits excellent spheroidal weathering, is preserved in the depression of a saucer-shaped structural basin. The Aguja beds within 10 feet below the igneous contact have been metamorphosed to a dark rusty reddish-brown quartzite, which forms the rim of the saucer. Pelecypods are not obliterated in the quartzites, and ordinary indurated to friable Aguja sandstone with cone-in-cone structures, petrified wood, and gypsum is present below the metamorphosed section.

Fossils: The only *original* organic remains collected from the Aguja are oyster shells, fish teeth, and fragments of reptilian bones, armor plates, and turtle shells. All other fossils consist of internal and external molds, the identification of which is indefinite. A tentative list of fossils collected from several localities follows:

North end of south Pitahaya Hill—
- *Ostrea* sp. (large, elongate)
- *Volutomorpha?*

Two miles east of Clanton ranch—
- *Ostrea* sp.
- *Corbula?*
- *Inoceramus?*
- Small indeterminate ribbed pelecypod
- *Natica?*
- *Volutomorpha?*

Halfway up south end of north Pitahaya Hill—
- *Volutomorpha?*

South of Half Dome—
- *Ostrea* spp.
- Fucoids
- Teeth of *Lamna texana*

South of Hill 4142 (SE)—
- Fragments of dinosaur bones
- Fragments of dinosaur armor plates

Prolific fossil bed halfway up fault scarp half a mile west of Hill 4142 (SE)—
Ostrea sp.
Numerous internal molds of a medium-sized pelecypod
Cardium?
Turritella trilira Conrad
Natica sp.
Volutomorpha? spp.
Calliomphalus?
Other impressions and molds of gastropods
Baculites sp.
Lamna texana tooth

STRATIGRAPHIC RELATIONS: The contact of the Aguja with the underlying Terlingua is gradational. Wherever the Aguja is overlain by Tertiary rocks, the contact is distinctly marked by an unconformity which is angular in some localities and apparently disconformable in others.

In his unpublished "Notes on the stratigraphy of the Upper Cretaceous formations of the Big Bend area, Texas," Stephenson (1948) stated: "I was not able to find any fossils in the upper Aguja that suggest an age as young as Navarro." Although composed of poor specimens, the suite of fossils collected from the Aguja in the Agua Fria area indicates Taylor age. The writer is of the opinion that no Cretaceous beds in the Agua Fria quadrangle are younger than Taylor.

Tertiary

General description.—The Tertiary rocks of the Agua Fria area consist of a volcanic series, principally calcareous tuff. Conglomerate, sandstone, breccia, fresh-water limestone, and intercalated lava flows occur in subordinate amounts. Nonmarine fossils collected from calcareous tuff and limestone beds indicate that some of the stratified section was deposited in fresh-water lakes. Change in thickness of beds and in lateral and vertical facies characterizes the tuff section (Pl. 3, fig. 3).

Buck Hill volcanic series.—The name Buck Hill volcanic series was applied by Goldich and Elms (1949, p. 1143–1163) to the Tertiary volcanic succession, 3000–4000 feet thick, that lies unconformably on Cretaceous strata in the area between the Alpine intrusive igneous center on the north and the Terlingua center to the south, and which extends into the Agua Fria quadrangle. Goldich and Seward (1948, p. 10–36) and Goldich and Elms (1949) divide the Buck Hill volcanic series into three formations:

Tascotal formation	1000± feet
Duff formation	1000–1400 feet
Pruett formation	900–1000 feet

The Pruett formation consists chiefly of well-indurated, thick to thin-bedded, commonly calcareous tuff that is normally grayish-white to bluish-gray or may be variegated and banded in many colors. The tuff section includes conglomerate, tuffaceous sandstone and breccia, tuffaceous fresh-water limestone, and interfingering lava flows. The base of the Pruett generally is marked by a limestone pebble conglomerate and conglomeratic arkosic sandstone. Goldich and Elms assign the Pruett formation, in part at least, to the Eocene.

The Duff formation is composed primarily of well-lithified, grayish-white but commonly variegated, massive to thin-bedded, rhyolitic tuff with subordinate amounts of sandstone, breccia, and conglomerate. The Duff tuff is essentially noncalcareous, and no fresh-water limestone has been found. The formation is probably Oligocene in age.

The lower part of the Tascotal formation consists of glaring white, thin-bedded, flaggy, sandy tuff. The upper part includes gray-buff, cross-bedded, coarse-grained, tuffaceous sand with minor amounts of breccia and conglomerate. The age is Oligocene (?) or younger.

Goldich and Elms (1949, p. 1145) correlated the Buck Hill volcanic series, in part, with the 2000 feet of tuffaceous sediments in the Chisos Mountains described by Udden (1907b, p. 60–66) as the Chisos beds and with the 3500-foot thick Squaw Peak volcanic series in the Quitman Mountains described by Huffington (1943, p. 1027–1046). Huffington assigned this volcanic section to the lower Tertiary, Eocene or Oligocene.

In the Agua Fria quadrangle, only the lower part of the Buck Hill volcanic series is present. Most of the rocks are Pruett with possibly a partial section of Duff. The sequence is referred to only as the Buck Hill volcanic series and is not divided. In the Buck Hill quadrangle, formation boundaries were established on lava

flows and lithologic characters not present in the Agua Fria quadrangle. In addition, exposures are inadequate to permit tracing of individual beds or zones into the quadrangle or to make possible the measurement of a composite section.

OUTCROP: The Buck Hill volcanic series, at most places capped by Quaternary gravel, is confined almost entirely to a north-south strip, which lies between longitudes 103°40′ and 103°45′ W. Owing to gentle westerly regional dip of the Tertiary tuff, progressively younger strata are encountered to the west. Outliers of the basal Tertiary conglomerate are not uncommon in other parts of the quadrangle; but, as a general rule, very few are found northeast of a line connecting Camels Hump (SE) with Hale Cabin (NC).

Because the tuffs erode relatively easily, sections of greatest thickness are preserved where tuff is protected by a gravel cover or an igneous cap. The tuffs formerly extended farther east and probably covered the entire quadrangle, but erosion has almost stripped them from the eastern two-thirds of the area.

THICKNESS: Goldich and Seward (1948, p. 15) state that "the cumulative thickness of the Tertiary volcanic succession is well over 3000 feet." The Buck Hill volcanic series is not this thick in the Agua Fria quadrangle, but 1000 feet is considered a fairly reasonable estimate.

BASAL TERTIARY CONGLOMERATE: The basal Tertiary or basal Pruett conglomerate is the most persistent member of the volcanic section in the Agua Fria quadrangle; an angular unconformity separates it from the underlying Cretaceous strata. The conglomerate, in its most abundant type, consists of well-rounded pebbles and cobbles of hard, gray Comanche limestones. The fragments, some of which contain siliceous oölites and silicified fossils, are tightly cemented in a gray to brown, coarse-grained, sandy matrix. More angular pebbles of brown and black chert are less abundant, and Gulf Cretaceous materials are present locally. This type of conglomerate is common in the northwest part of the quadrangle.

No igneous pebbles were observed in the basal Pruett conglomerate. This suggests that the igneous centers either were non-existent or had not yet been uncovered at the time the basal conglomerate was deposited. Conglomerates and breccias higher in the tuff series contain notable percentages of igneous fragments.

Remnants of the basal Tertiary conglomerate are widespread, and presumably it once covered the entire quadrangle. Loose, rounded pebbles and cobbles are abundant in spots in the southeast corner of the area. *Orbitolina texana* Roemer, which indicates a Glen Rose source, is abundant in some of the rounded fragments. On the northeast flank of Hill 4142, a bench or terrace in the Aguja is held up by a tightly cemented cap of the conglomerate.

An unusual development of the conglomerate occurs on the west flank of Hill 4207 (SW) and extends westward into the Tascotal Mesa quadrangle. Most of the pebbles, cobbles, and boulders (some more than a foot in diameter) are fragments of a very hard, coarsely crystalline, white or gray to light-brown limestone that contains gray to brown flint nodules and silicified colonial corals, branching corals, rudistids, and *Cerithium*. The siliceous material stands out in relief, and the faunal assemblage suggests the Edwards equivalent of the Devils River as a source. The conglomerate also contains chert and flint pebbles. At Hill 4207, the few feet of conglomerate rests on the Boquillas flags; but within a half mile to the west, due to the strong east dip of the Comanche section, remnants of the tightly cemented conglomerate cap the Buda limestone, then the Grayson marl (on which the conglomerate slumps), and still farther west the conglomerate rests on uppermost Devils River limestone. Because the conglomerate dips to the east at a gentler rate than the Cretaceous strata, the Cretaceous-Tertiary unconformity is markedly angular in this area.

Some modification from the typical basal Pruett conglomerate occurs in the central part of the quadrangle. In the small hill half a mile northwest of Cheosa Waterhole (C), about 15 feet of the conglomerate caps Terlingua beds. The lower 5 feet consists of the regular rounded limestone pebbles and cobbles plus angular boulders of Aguja sandstone, 1 to 3 feet in maximum dimension, tightly cemented in a sandstone matrix. About 5 feet of the typical conglomerate lies above the Aguja boulders,

the angularity of which indicates little transport and a local source. The uppermost 5 feet is a coarse, cross-bedded sandstone with thin conglomeratic layers. Possibly an old land surface on which there were residual Aguja boulders subsided, and then torrential streams deposited the typical basal Pruett conglomerate.

The prominent cuesta 1 mile southwest of B.M. 3540 (C) is capped by the resistant basal Tertiary section. The lowermost beds are coarse-grained sandstone, which, like the underlying Terlingua beds, is highly gypsiferous. Most of the pebbles and cobbles in the conglomerate above the basal sandstone are well-rounded, dark-gray limestones that contain *Orbitolina texana* Roemer, chert, and silicified fossils. These indicate Glen Rose and Devils River sources. Minor amounts of black, brown, and banded chert, petrified wood, and limestone pebbles with small siliceous concretions also are present.

The basal Tertiary conglomerate caps Terlingua in the hills 1¼–2 miles northeast of Whistler Squat (SW). The grayish conglomerate is about 2 to 3 feet thick and is composed largely of locally derived Terlingua materials, such as white chalky limestone fragments up to 3± inches in greatest dimension, fragments of *Inoceramus*, and almost complete specimens of *Durania*. A few pebbles of light- to dark-brown banded chert are present. Several feet of gray to light rusty brown, thin-bedded and platy sandstone-breccia lie above the conglomerate.

On the upthrown side and near the northwest extremity of the Fizzle Flat fault, the basal Tertiary is represented by 2 to 3 feet of indurated, rusty gray to reddish-brown, thin-bedded to platy, coarse-grained sandstone. The basal few inches are a sandstone-breccia-conglomerate with limestone pebbles, up to pecan size, probably derived locally from the underlying limestone beds in the Terlingua formation.

The lowermost Tertiary beds are exposed rather extensively about half a mile northwest of Agua Fria Mountain. Fairly typical basal Pruett conglomerate rests on Aguja, and the two are separated by a gently waving unconformity clearly marked by a 2 to 3-inch bed of gypsiferous, limonitic material that contains yellow ochre. A thick section of coarse, gray, cross-bedded sandstone with some breccia rests on the conglomerate. The numerous holes and small caves that weather into this sandstone provide shelter for small animals and give the cliff face an eerie appearance. The conglomeratic section averages 10 feet thick and consists of lenses of conglomerate ranging from a few inches to 2 feet thick. The average pebble size is 1 inch, and the percentage of dark-gray to black chert associated with the dark-gray Comanche limestone pebbles is relatively high. *Inoceramus* prisms are present in the conglomerate, and at some places lenses of creamy yellow, coarse-grained, cross-bedded sandstone are separated by thin seams of impure sandy clay.

Isolated outcrops of the basal Pruett conglomerate immediately north of the Tascotal Mesa fault in the southwest part of the quadrangle cap uppermost Terlingua, the Terlingua-Aguja transition zone, or basal Aguja. The conglomerate reaches a thickness of about 25 feet in the westernmost of these outcrops. The patch of conglomerate 1¼ miles due south of Whistler Squat yields many fragments of petrified wood. The conglomerate is underlain by about 5 feet of friable, yellow-gray, irregularly bedded, coarse-grained sandstone, the lower 1 foot of which is locally a coquina of reworked Cretaceous fossils. The thickness of the conglomerate about a mile southeast of Whistler Squat averages 10 feet, but in places it reaches 20 feet. Very coarse quartzitic sandstone is present as lenses and cementing material in the typical conglomerate. A number of the cobbles are large fragments of poorly rounded Gulf Cretaceous limestone that contains abundant *Inoceramus* shells up to 5 inches in diameter.

The thickest basal Tertiary conglomerate observed occurs in the southwest part of the quadrangle slightly more than a mile northeast of the Solitario fault. Proximity to the Solitario probably accounts for this excessive thickness. The 40- to 50-foot conglomerate section is exposed in an upthrown block at the intersection of two faults 2 miles south-southwest of Whistler Squat. On the fault scarp that faces southwest, typical conglomerate and associated sandstone lenses, reworked Cretaceous

materials, and scattered petrified tree trunks appear. The conglomerate is so tightly cemented that pebbles, cobbles, and sandy cementing material fracture alike. Thus relatively smooth, clean breaks result from faulting.

At a point on the north bank of Alamo de Cesario Creek 1¼ miles east of Whistler Squat, the gray Terlingua clay-shales are capped unconformably by basal Tertiary gray-brown, cross-bedded, coarse-grained sandstone with some breccia. The wavy unconformity is marked by a brownish, calcareous, gypsiferous, limonitic secondary material.

In a relatively small, almost circular structural basin about half a mile west of Hill 3494 (SC), the following section is preserved.

5. Tuff.
4. Sandstones and sandy clay.....50–60 feet
3. Basal Tertiary conglomerate.....10–12 feet

Unconformity

2. Upper Terlingua.....50 feet
1. Giant *Inoceramus* beds.

The basal conglomerate is typical except that most pebbles are relatively small—less than 3 inches in diameter. The sandstone and sandy clay section above the conglomerate is rusty brown. The coarser materials of unit 4 are poorly sorted; they range from fine-grained sandstone to sandstone-breccia, and some are cross-bedded. The clayey portion of unit 4 consists of yellow-gray silty clay-shale with nodules and veins of rusty gypsum in cracks and joints. A white efflorescence spottily crusts the surface of the sandy clay. This section resembles some of the Gulf Cretaceous beds, particularly the Aguja; and it suggests a partial derivation of the sandy clay from the weathering and reworking of Aguja and upper Terlingua beds. This sequence is essentially the same as that along the Agua Fria ranch road northwest of Agua Fria Mountain.

The derivation of conglomeratic materials from both local and distant sources is illustrated by the basal Tertiary conglomerate exposed in the bed of Terlingua Creek due east of Paint Mountain. Petrified tree trunks up to 15 inches in diameter and 2+ feet long, ironstone concretions and boulders up to 1.5 feet in diameter, septaria, and fragments of impure limestone that contain cone-in-cone structures presumably were derived locally from the underlying Aguja. Minor quantities of pebbles and cobbles of chert, jasper, and chalcedony indicate a more distant source, for these materials are not characteristic of the Aguja.

In Hill 3494 (SC), about 10 feet of Aguja is preserved under the Cretaceous-Tertiary unconformity, which is marked by secondary rusty brown gypsum. A thin atypical basal conglomerate, nowhere over a few feet thick, was observed. Rusty brown, angular Aguja fragments with minor amounts of limy nodules and concretions are incorporated in a sandy matrix. Thick beds of brownish-gray, coarse-grained, cross-bedded sandstone-breccia lie above the unusual basal conglomerate and substitute for it where it is absent. These lower Tertiary sandstone-breccias include many fragments of petrified wood, and the sequence continues up to the base of the flows (?) that cap the hill.

Reworked *Gryphaea* and *Inoceramus* prisms occur in the basal brownish-gray, coarse-grained sandstone portion of the conglomerate section on Cat Draw (C and WC). Angular fragments of black chert, of coarse-grained sand to pebble size, are present in both the basal sandstone beds and the sandy matrix of the overlying typical conglomerates. This section rests unconformably on the upper Terlingua.

The basal Tertiary conglomerate everywhere rests unconformably on Cretaceous strata, and it is in contact with every Cretaceous formation exposed in the Agua Fria quadrangle. Thus, from a regional viewpoint, the Cretaceous-Tertiary unconformity is angular; but there are local areas in which the discrepancy in dip of the two systems is so slight that the break is more appropriately termed a disconformity.

A diagrammatic north-south cross section drawn from the south part of the Buck Hill quadrangle through the Agua Fria quadrangle would show the following regional relationships between Cretaceous and Tertiary beds. In the Buck Hill quadrangle at Stop 3, Goldich and Seward (1948, p. 27) report the basal Tertiary as largely sandstone with little conglomerate that lies unconformably on the Boquillas limestone. A thickness of 2–4 feet

is listed for the conglomerate-sandstone here. Farther to the south, in the north-central part of the Agua Fria quadrangle, the typical conglomerate thickens to 10–15 feet and rests unconformably on the Fizzle Flat lentil and slightly higher beds of the upper Boquillas-Terlingua unit. In the central part of the quadrangle, the sandstone-breccia-conglomerate includes locally derived angular Aguja boulders and rests on upper Terlingua beds. South of the Fizzle Flat fault, the conglomerate contains many products reworked from the Aguja, and it rests on either the Terlingua-Aguja transition zone or a thin section of Aguja. Near Paint Mountain (SC), the conglomerate rests unconformably on the Aguja and consists almost entirely of materials obtained from the Aguja section.

The typical conglomerate reaches a thickness up to 50 feet in the southwest part of the quadrangle near the Solitario. This suggests that an important contributor of Comanche fragments lay southwest of the Agua Fria area. The Solitario was already a positive element in early Tertiary time and had been eroded deeply enough for the Devils River and Glen Rose to be exposed and furnish materials for the conglomerate. Proof is the marked angular unconformity between the basal Tertiary conglomerate and the underlying Cretaceous west of Hill 4207 (extreme SW). At this locality, the conglomerate rests on a slightly tilted erosional surface that truncates strong east-dipping Devils River, Grayson, Buda, and Boquillas beds.

Exposures along several creeks in the area northwest of Agua Fria Mountain illustrate the irregularity of bottom on which the basal Tertiary conglomerate was deposited (Pl. 4, fig. 3). The resistant conglomerate forms overhanging ledges after the softer underlying Cretaceous strata, such as uppermost Terlingua and basal Aguja, have been eroded. The original broad undulations and pot-hole-like depressions are preserved as casts on the underside of the conglomerate.

Tuffs: The volcanic series above the basal conglomerate is a heterogeneous assortment of materials in which calcareous tuffs predominate. Conglomerates, breccias, sandstones, clay-tuffs, limestones, and lava flows are other constituents. Lenticularity of beds, unconformities, channeling with fill, and facies changes within short distances are common.

The tuffaceous beds in the Agua Fria quadrangle are dominantly white to gray, nodular, calcareous clay-tuffs, but pastel shades of cream, yellow, brown, red, pink, and purple are abundant. Thick, horizontal, brick- to brighter-red and gray bands alternate in the bluffs of Devils Graveyard.

The clay-tuff, especially the gray, is bentonitic in many places and gives rise to the clay balls found in creek beds. Bentonitic clay-tuff sections with few ledges of limestone, sandstone, breccia, or conglomerate produce characteristic whaleback hills (Pl. 3, fig. 1), but resistant beds are almost everywhere interbedded with the tuffs.

$CaCO_3$ supplies much of the cementing material of the tuffs and occurs as relatively rare, dense, limestone beds, generally 1–2 feet thick; zones of nodular limestone; and small nodules of impure limy material dispersed throughout the section. Presumably much of the $CaCO_3$ in the Pruett formation was obtained from the weathering of Cretaceous strata.

Glaring snow-white chalky tuff apparently was deposited as pockets in brick-red, calcareous clay-tuff. A series of these white pockets extends for more than a mile northeastward from Dike 3700 in Devils Graveyard. The alignment suggests faulting, but underlying uninterrupted key beds disprove a possible fault contact of the white and red tuffs.

Very coarse, grayish, sandstone-breccia channel deposits, lenticular in cross section, occur in the western part of the quadrangle, where, because of their resistant nature, they hold up elongate topographic ridges in the tuff section.

In many places intraformational conglomerates in the tuff occur in the form of discontinuous lenses that may be no greater than 1–3 feet thick. Many such conglomerates are composed entirely of well-rounded and highly polished chert pebbles and cobbles, which indicate a great horizontal distance of transport or a lateral reworking for considerable time. Other fragments found in the sandstone-conglomerate lenses are tuffaceous material,

limestone pebbles, green chert, and dark banded chert.

In the east-west draw about midway between Agua Fria Mountain and Whistler Squat, a small hill a quarter of a mile east of the road appears yellow-brown from a distance due to the weathering of numerous limonitic and calcareous concretionary structures from a brick-red clay-tuff section. The concretions range up to several inches in diameter, and some have a crude approach to cone-in-cone structure.

In Devils Graveyard, vertical clastic dikes, 1–3 inches thick and composed of angular fragments of varicolored tuffs in a darker matrix, are more indurated than the enclosing tuff and produce minor topographic ridges.

The recent works of Goldich and Elms (1949) and Goldich and Seward (1948) present a detailed description of the tuffs of the Buck Hill volcanic series in their normal stratigraphic sequence. Complex structure, lateral facies changes, and concealed intervals in the Agua Fria quadrangle prevented the tracing of individual beds and, consequently, the building up of a composite section. The following details are from local areas and stratigraphically isolated exposures, but they are presented in supposedly correct ascending order.

Petrified tree trunks are fairly common in the basal conglomerate and the sandstone or tuff that immediately overlies it. Knots, grain of the wood, and annular rings are beautifully preserved in some specimens. Several fossil trees in the vicinity of Hill 3580 (SW) are 50 to 70 feet long.

The lower tuff at several places closely resembles the underlying Aguja formation, particularly the tuff that rests on a coarse-grained sandstone commonly associated with the basal conglomerate. This tuffaceous section, like the Aguja, is generally yellow-brown to gray with rusty splotches. The striking similarity of the two formations is perhaps one reason earlier writers assumed a gradational contact between Cretaceous and Tertiary beds. Apparently the Aguja was reworked and redeposited with the basal tuff beds so that the resulting rock is a mixture of Aguja and Tertiary materials. The lower tuff, much of which is high in $CaCO_3$, clay, and sand content, generally is brownish or reddish to white, forms whaleback hills, has thin continuous sandstone beds and lenticular channels of sand, and in some places looks like Aguja that has been reddened by secondary action. The presence of the basal Pruett conglomerate below this questionable section is the most reliable proof that it is Tertiary rather than Cretaceous.

The tuffs exposed on Paint Mountain are relatively low in the Pruett section and are strikingly conspicuous, because the alternating thick, horizontal, reddish and grayish bands contrast sharply with the drab background color of the Aguja as the mountain is approached from the northeast. The tuff is well-lithified and highly calcareous, and large low-spired fossil snails were collected at the northeast base of the mountain. According to Goldich (personal communication), calcareous nodules present here are more numerous and larger than in the corresponding tuff in the Buck Hill quadrangle.

Barite occurs in the lower tuff at a locality 1½ miles west of Paint Mountain on the west bank of a draw that empties into Alamo de Cesario Creek.

Section of lower Buck Hill volcanic series measured on east bank of draw 1¾ miles due north of Whistler Squat

	Thickness Feet
Quaternary—	
19. Terrace gravel	6
—Unconformity—	
Tertiary—	
Buck Hill volcanic series—	
18. Hard, dirty pink-gray, calcareous sandstone bed; forms prominent ledge	1.5
17. Partially covered, friable, massively bedded, calcareous and tuffaceous silty clay with occasional hard, thin, ledge-forming tuff beds. Broad color bands grade upward from gray to brick-red to light purple to gray. Odd-shaped calcareous nodules weather out on slopes	63
16. White to light-purple tuffaceous section with beds, 1± foot thick, of hard,	

white, nodular, impure, pitted limestone that weathers rusty brown..... 21

15. Very hard, gray to reddish-brown, thick-bedded, calcareous, fine-grained sandstone; weathers to well-rounded boulders..... 6

14. Hard to friable, light greenish-gray, massively bedded calcareous sandstone with occasional layers of chert-pebble conglomerate. Unit forms precipitous cliff and varies considerably in thickness..... 25±

13. Friable to indurated, light-purple, calcareous and tuffaceous beds..... 5

12. Very hard, white, nodular, impure tuffaceous limestone that weathers rusty brown..... 8

11. Alternating calcareous tuffs and calcareous siltstones. Tuff beds average 3 feet thick and are light gray to reddish-lavender. Siltstone beds are hard, white, average 1.5 feet thick, and weather to a rusty color and nodular surfaces..... 40

10. Hard, white tuff bed..... 0.5

9. Indurated, grayish-white, massively bedded calcareous tuff..... 4

8. Hard, white, calcareous tuff bed..... 0.5

7. Hard, light grayish-white, massively bedded, noncalcareous tuff..... 12

6. Very hard, white tuff bed with small brown concretionary structures..... 0.5

5. Hard, rusty orange to reddish-lavender to grayish-white, calcareous, tuffaceous clay with zone of calcareous nodules. Section weathers to whaleback hills with nodules and small cauliflower concretions (caliche?) on slopes..... 25

4. Hard, gray-brown, laminated, fine-grained calcareous sandstone beds, 3–4 inches thick, alternate with reddish, calcareous siltstone beds, 1 foot thick.. 7

3. Hard to friable, dingy gray, poorly bedded, coarse-grained calcareous sandstone..... 2.5

Total tuffaceous section exposed. 221.5

——————Unconformity——————

Cretaceous—

Terlingua beds—

2. Hard to indurated, gray to rusty yellow, laminated calcareous shale..... ± 5

1. Bottom of draw.

Owing to gentle westerly dip, the tuffaceous section in Devils Graveyard is tentatively regarded as middle Pruett. Outcrops in the semicircular hill northeast of Whistler Squat (Pl. 3, fig. 3) illustrate the approach to a provisional age determination of such isolated exposures. A conglomerate that contains many igneous pebbles lenses out completely in places and lies on an unconformity of variable position in the tuff section. The igneous pebbles, some amygdaloidal, indicate that the conglomerate is younger than basal Pruett. Although the tuff above the unconformity or conglomerate is decidedly different lithologically and in bedding from that below, thereby suggesting a younger formation, the entire sequence is probably Pruett, because all the tuffs are calcareous.

A persistent light-colored sandstone marker bed that extends from the northwest corner of the area southward about to the latitude of Burnt House Camp may correspond to the upper [Whirlwind] breccia member of the Pruett formation. The sandstone bed dips gently to the west and is continuous along the west bank of the tributary which flows from the north and empties into Crystal Creek.

With structural conditions for chief evidence, the youngest beds of the Buck Hill volcanic series probably are those in the southwest part of the area just northeast of the Solitario fault. The sequence is:

Tuff
Lava flow
Tuff
Lava flow
Highly colored tuff (50± feet)
Fresh-water limestone (50± feet)
Very coarse yellow conglomerate (200± feet)
Tuff

The brilliantly colored tuff above the limestone displays olive-green, cream, white, light brown, rust, red, purple, and yellowish-green.

WELDED TUFF: At Hill 4014, nearly half a mile southwest of Agua Fria Mountain, the rock that caps the ordinary tuff is a welded tuff resembling rhyolite. Macroscopically the rock appears to be a porphyry with phenocrysts of clear feldspar and quartz set in a salmon-pink aphanitic groundmass. Inclusions of a pumiceous rock, up to 4 inches in greatest dimension, are common.

Thin sections show lune-, cusp-, and bubble-shaped structures in a pasty groundmass. Some of the relict bubble-like structures are collapsed, which suggests that pumice plus heat produced the collapsed pumice effect. The angular shard-like structures, however, are convincing evidence for a pyroclastic origin; and the rock probably is a welded tuff (Mansfield and Ross, 1935) or an incandescent tuff (Fenner, 1948). Because euhedral to subhedral, embayed and corroded crystals of sanidine and quartz, up to 2.5 mm long, and fragments of a pre-existing rock are present in the welded glassy matrix, the rock might appropriately be called a welded vitric-crystal-lithic tuff.

Other outcrops of this rock occur from the Mesquite Tank area northwestward to the point where the Tascotal Mesa fault intersects the west boundary of the quadrangle. Lonsdale (1940, p. 1563) described a welded tuffaceous rock from the Tertiary section southwest of the Solitario. Recent uncompleted work by Goldich, Erickson, and others indicates that rocks of this kind may be widespread in Trans-Pecos Texas.

FRESH-WATER LIMESTONE: Goldich and Elms (1949, p. 1143–1151) pointed out that the Buck Hill volcanic series, although chiefly tuff, includes a subordinate amount of fresh-water limestone. The limestone beds yield fossils well enough preserved to be identified accurately and thereby afford a fairly reliable age determination for the otherwise dominantly clastic Tertiary section.

Limestones of the Buck Hill volcanic series are exposed at a number of isolated localities in the Agua Fria quadrangle. During the summer of 1948, Goldich visited many of these limestones and concluded that all are of fresh-water origin. Most contain a fresh-water fauna, but some are nonfossiliferous. The latter cannot unquestionably be called fresh-water, but their presence in a volcanic section that has yielded land snails and their close association with and lithologic similarity to fresh-water limestone beds are indirect evidence for nonmarine conditions of deposition.

Many of the Tertiary limestone beds are lithologically similar to normal marine limestone but contain the fresh-water genera *Planorbis* (verified by H. B. Stenzel) and *Goniobasis* (verified by Goldich). According to S. P. Ellison (personal communication), the internal molds of ostracodes obtained from a limestone of the Buck Hill volcanic series probably represent fresh-water forms. Goldich and Elms (1949, Fig. 3) list *Goniobasis*, *Physa*, *Cochliopa*, ostracodes, charophytes, and algal structures from fresh-water limestones in the Pruett formation; and they find fossil snails scattered in the tuffs of the Pruett and Duff formations.

The hill on top of which is B.M. 3540 (C) is capped by 41 feet of macroscopically nonfossiliferous Tertiary limestone, which rests directly on the Fizzle Flat lentil, here reddish to pink and silty. From a distance, the massive limestone might be mistaken for a reef in the Boquillas-Terlingua sequence. The rock ranges from very dense to a powdery, chalky material. More generally, though, this limestone is hard to very hard, light brown to gray, massively and irregularly bedded; and it contains small amounts of scattered light-brown chert and limonite. A very rough and irregular (karren) weathering surface characterizes the limestone. Some portions of the rock appear brecciated, which may account for the development of a cracked type of weathering. Samples of a white, granular or saccharoidal caliche-like phase of the limestone, common on top of the hill, have a petroliferous odor and possibly contain ostracodes. Many veins of white calcite are present in this circular Tertiary limestone mass, which apparently occupies a small, local, saucer-shaped structural basin, for the Fizzle Flat beds dip under the base of the limestone at all points around the hill. This may, however, be merely the result of settling.

Rocks similar to those just described occur west of Hill 4207 (SW) where a few feet of

Tertiary limestone rests directly on the basal Pruett conglomerate. The limestone contains some chert, exhibits the cracked type of weathering, and closely resembles the Devils River limestone.

A dirty brown limestone bed, 4 feet thick, that yields the best silicified Tertiary fresh-water fossils in the area, caps a section of white to light-gray calcareous tuff in a small hill just north of the road 2 miles north-northeast of Burnt House Camp (NW). Several other outliers of hard, white to brown fresh-water limestone occur in the fault blocks southeast of this locality and east of Burnt House Camp. Light-gray to light-brown chert and gray-brown flint are present in some of these resistant limestone beds, which average 2.5 feet thick. Many beds weather to nodules and boulders, and some are fossiliferous.

Section measured on south face of small hill northwest of broad right angle curve in road 2 miles north-northeast of Burnt House Camp

	Thickness *Feet*
Buck Hill volcanic series—	
5. Very hard, brownish-gray to brown, thick bed of fresh-water limestone. Contains chert, flint, and silicified fossils (*Goniobasis* most abundant, *Planorbis*, ostracodes). Weathered rock is brown, has a cracked appearance, and breaks down to very angular fragments.	4
4. Covered (apparently same as 2)	34
3. Hard, white to light-gray fresh-water limestone bed. Weathers to very nodular surface and contains brown chert. Fossiliferous	2.5
2. Friable, light-gray, massively bedded clayey tuff. Slope weathers to nodular surface	13
1. Valley flat.	

A nonfossiliferous Tertiary limestone, probably the same as that at Hill B.M. 3540 (C), caps Hill 3546, 1½ miles to the southeast. If these two limestones could be proved correlative, the date of faulting in this locality could be determined more accurately. The diastrophic history of this area is discussed later.

Section measured at southeast end of Hill 3546 (C)

	Thickness *Feet*
Tertiary—	
Buck Hill volcanic series—	
7. Hard, snow-white to brown, massive and irregularly bedded nonfossiliferous limestone. Smooth-textured to granular, karren and cracked weathering, small amounts of limonite and chert	40±
6. Partially covered slope of reddish tuffaceous section	38
5. Hard, rusty gray to gray, massive and cross-bedded calcareous sandstone-breccia	20
4. Indurated to friable, gray to yellow, massively bedded tuffaceous marl with dull brick-red splotches. Hard irregular nodules weather out	25
3. Basal Tertiary conglomerate: Hard, yellowish-gray conglomerate beds, 3± feet thick, consist of well-rounded limestone and chert pebbles (up to 4 inches in greatest dimension) cemented in a calcareous sandy matrix. These alternate with hard to friable, yellow-gray, cross-bedded, coarse-grained calcareous sandstone beds, 2± feet thick. Limonitic zone occurs 2 to 3 inches above disconformity, and *Inoceramus* prisms common in this conglomeratic section	16
——————Unconformity——————	
Cretaceous—	
Terlingua beds—	
2. Indurated to friable, gray to cream-yellow, laminated calcareous shale. Weathers to small splinters and biscuit-shaped nodules. Limestone beds, about 6 inches thick, widely spaced	57
1. Top of Fizzle Flat lentil (?).	

A nonfossiliferous Tertiary limestone, which contains pebbles of black chert, caps the tuffs that form the south bank of an easterly sloping draw at a point west of the road and 2 miles northwest of Agua Fria Mountain. Another

nonfossiliferous limestone is present in the Tascotal Mesa fault zone 1 mile east of the west boundary of the quadrangle where a bed about 3 feet thick caps the tuffs in a small hill.

The thickest development of limestone in the Buck Hill volcanic series (Pl. 4, fig. 2) occurs in the conglomerate, tuff, and lava flow sequence just northeast of the Solitario fault (SW). This limestone section, which is approximately 50 feet thick and thins somewhat to the northwest, rests on a section of yellow conglomerate some 200 feet thick. The impure granular or saccharoidal limestone is indurated to hard, yellow-gray, thin and irregularly bedded. Imperfect karren, pitted, and cracked types of weathering prevail. The limestone contains geodes, algal structures, and angular black chert pebbles. The latter resemble the bedded cherts of the Ordovician Maravillas formation, which is exposed in the Solitario and may have been the source of the black fragments. Cave-type deposits form where there are overhanging ledges of the limestone. The rock disintegrates into small angular fragments that make steep dip-slopes difficult and dangerous to walk on; the dips in this area average 25° to the southwest. Certain zones carry finely disseminated dark-brown chert in thin, irregular layers, some of which contain algal structures.

YELLOW CONGLOMERATE: A thick yellow conglomerate crops out in a band in the downthrown (northeast) block of the Solitario fault, and this band parallels the fault for almost its entire length in the quadrangle. The rocks here are among the youngest Tertiary exposed in the quadrangle, and probably the conglomerate is near the top of the Pruett. The conglomerate, apparently a local development around the periphery of the Solitario, is overlain by limestone, tuff, and lava flows. The 50 feet of limestone resting on the conglomerate strongly suggests that the latter is part of the Pruett formation.

The yellow conglomerate varies considerably in thickness. From exposures in the vertical walls of a huge plunge basin in the area southwest and west of Hill 3963, the thickness was estimated at 200–300 feet. The conglomerate, like the limestone, tuff, and lava flows of this sequence, thins to the northwest so that it is probably no more than 100 feet thick at the west boundary of the area.

The basal portion of the conglomerate, which rests on a wavy and channeled surface of the underlying tuff, consists primarily of fairly well-rounded igneous boulders that average a foot in diameter, but some up to 4 feet were observed. Local lenses have a high percentage of angular boulders and should be termed breccia-conglomerates. Limestone boulders, some of which contain black (Maravillas?) chert, are also present.

The conglomerate in the vicinity of Hill 3951 and Hill 3802 is loose to indurated, yellow, and massively bedded. The matrix is a fine-grained yellow sand with much gypsum and other efflorescences. Pebbles, cobbles, and boulders consist of angular igneous rocks to well-rounded limestones. The size range is from that of a small pebble to boulders 3± feet in diameter. The fragments consist of Comanche limestones with silicified fossils, fine-grained dense to vesicular acidic igneous rocks, quartz, black Maravillas (?) chert, Caballos (?) novaculite, green and brown cherts, and banded cherts. These suggest local derivation from the Solitario, which lies to the southwest; and the angular chert and novaculite fragments impart a Paleozoic aspect to a weathered surface of the conglomerate. On relatively flat weathering surfaces, brecciated sponge-like caliche deposits, 3± feet thick, occur locally.

PLATE 4.—BUCK HILL VOLCANIC SERIES

FIGURE 1. VIEW SOUTHEASTWARD ACROSS THE TUFF SECTION OF DEVILS GRAVEYARD TOWARD AGUA FRIA MOUNTAIN

Dike 3600 in foreground. (Photograph by R. B. Davis.)

FIGURE 2. FIFTY-FOOT SECTION OF FRESH-WATER LIMESTONE UNDERLAIN BY YELLOW CONGLOMERATE AND OVERLAIN BY TUFF AND LAVA FLOWS

Dip is southwest toward Solitario fault.

FIGURE 3. CRETACEOUS-TERTIARY CONTACT

Basal tertiary conglomerate was deposited on irregularly eroded Terlingua beds in southwestern part of quadrangle.

FIGURE 1

FIGURE 2

FIGURE 3

BUCK HILL VOLCANIC SERIES

In most places the conglomerate rests directly on ordinary tuff. However, at a point a mile due west of Hill 3963, marked by the intersection of southeasterly and northeasterly sloping draws and in the southeast bank of the latter, a welded tuff averaging 10 feet thick lies between regular tuff below and the yellow conglomerate above. The welded tuff dips upstream (southwest) toward the Solitario, and within a quarter of a mile it is both overlain and underlain by the yellow conglomerate. These conditions suggest that the Solitario was rejuvenated while the yellow conglomerate was being deposited and that the doming of the Solitario proper was accompanied by a periphery collapse in which the conglomerate accumulated as boulders were shed from the Solitario dome. Then the welded tuff was formed on top of ordinary tuff to the northeast, but to the southwest it accumulated on the lower portion of the conglomerate already deposited nearest the Solitario. Later a great thickness of the yellow conglomerate was deposited above the welded tuff. Materials in the conglomerate indicate Paleozoic, Comanche, and igneous sources. Because these rocks are exposed in the Solitario, it is a likely source area. The decrease in fragment size from bottom to top, illustrated by gradation from very coarse basal material to the uppermost sand and finer breccia-conglomerate, suggests that the Solitario was being worn down during the accumulation of the yellow conglomerate.

LAVA FLOWS: Intercalated lava flows are an integral part of the Buck Hill volcanic series. Sheetlike igneous masses are common in both Cretaceous and Tertiary strata of the area, but most tabular igneous masses in the Cretaceous, whether deroofed or covered, are sills, whereas those in the Buck Hill volcanic series are mostly flows. Probably all igneous rocks in the Agua Fria quadrangle are of Tertiary age.

Two trachyte flows separated by tuff cap Paint Mountain. Both exhibit flow structure, and both include basal flow breccias preserved in old channels in the tuffs under the flows. The upper reddish-brown flow is vesicular, and some of the vesicles contain calcite amygdules.

Two flows at a higher stratigraphic position are separated by conglomeratic tuff and are faulted down against the Boquillas along the Solitario fault. The northwest-southeast extent of these outcrops is some 2½ miles. The lower flow is a vesicular trachyandesite or andesine trachyte with agate amygdules. The higher flow is a more dense analcimitic diabasic microgabbro with vesicular and amygdaloidal portions.

Basic analcime-bearing rocks occur as flows in the volcanic section at Hill 3494 (SC) and in the area southwest of Agua Fria Mountain.

FOSSILS: The only fossils obtained directly from the tuff are several internal molds of a low-spired *Helix*-like gastropod. The largest specimen is 1¼ inches in diameter, 1 inch high, and consists of 4 whorls. The snails were collected from white, nodular, calcareous tuff beds at the northeast base of Paint Mountain. These beds probably occupy a lower Pruett stratigraphic position, for, although the interval between the two localities is covered, the basal Pruett conglomerate crops out in the bed of Terlingua Creek about a quarter of a mile east of this fossil locality, and the east-west dip component between the two points is slight.

Limestones, where fossiliferous, are the most prolific fossil beds of the Buck Hill volcanic series. Well-preserved specimens of silicified forms were collected from the limestone that caps the small hill just northwest of the road and 0.4 mile northwest of Hill 3550 (NW). The white fossils stand out in relief on surfaces of the hard, dark-brown limestone. Although small, the gastropods are conspicuous by color contrast. An insoluble residue of this limestone contained:

Goniobasis sp.
Planorbis sp.
Internal molds of ostracodes

Goniobasis and *Planorbis* are listed as nonmarine mollusca by Henderson (1935); and according to S. P. Ellison (personal communication) the ostracodes are probably fresh-water forms. A hard, light-gray, chert-bearing 2.5-foot thick bed of fresh-water limestone, 34 feet below the bed just described, contains numerous *Planorbis* sp. The largest specimen found is 0.2 inch in diameter.

Several other hard, light-gray limestone beds in the northwest part of the quadrangle, and particularly the steeply dipping bed just north of the road and in the fault zone at a point almost three-fourths of a mile due south of Long Hills, yield numerous *Planorbis* sp. These

forms are preserved as casts of clear to brown calcite. The largest specimens reach half an inch in diameter and consist of 6 or 7 whorls. These beds are low in the Buck Hill volcanic series, probably lower Pruett.

Limestone beds from a high (?) stratigraphic position in the Pruett (?) formation in the area just northeast of the Solitario fault contain algal structures that average half an inch in diameter.

STRATIGRAPHIC RELATIONS: Goldich and Elms (1949, p. 1143–1145) tentatively assign the Pruett formation to the Eocene on the basis of abundant specimens of *Goniobasis* collected from limestone lentils in the upper part of the formation. They assign the Duff formation to the Oligocene on the basis of a smaller gastropod. Because the Buck Hill volcanic series of the Agua Fria quadrangle can be correlated with that of the Buck Hill area, the next quadrangle to the north, the Tertiary volcanic rocks of the Agua Fria quadrangle are likewise tentatively assigned to the Eocene-Oligocene.

The basal conglomerate of the Buck Hill volcanic series in the Agua Fria quadrangle everywhere rests unconformably on Cretaceous strata. A relatively thin (Quaternary?) gravel cover unconformably caps the tuffaceous series in several large areas.

Quaternary

General description.—Deposits of Quaternary age in the Agua Fria quadrangle include older gravels that stand at higher altitudes in the western part of the area and alluvium or valley-fill found at lower elevations in the eastern part of the quadrangle. The two were mapped as separate units.

Gravel.—The Quaternary (?) gravels consist chiefly of fairly well-rounded cobbles and boulders of igneous rocks that occur in relatively thin, almost flat-lying sheets at different elevations. Three distinct gravel-covered rock terraces can be seen west of Terlingua Creek near Clanton ranch. The approximate locations and elevations of the three main terraces are:

Terrace	*Approximate distance west of Clanton ranch*	*Approximate elevation, feet*
I	1¼ miles	3300
II	½ mile	3250
III	¼ mile	3200

As a reference surface, the elevation of the present flood plain of Terlingua Creek, less than a quarter mile west of Clanton ranch, is about 3175 feet.

The oldest gravels cap Long Hills (NW) at an average elevation of about 3700 feet. Green Valley or Greasewood Flat, the most widespread gravel-covered surface in the northwest part of the quadrangle, averages about 3550 feet in elevation. The youngest terrace, about 25 feet lower than Greasewood Flat, parallels the present course of Terlingua Creek and is relatively narrow. This youngest gravel deposit, which can be called the Burnt House Camp terrace, is some 25 feet higher in elevation than the present flood plain.

Apparently Green Valley, which is now being dissected by Terlingua Creek and its tributaries, is an extensive pediment that developed as Bandera Mesa, in the Tascotal Mesa quadrangle to the west, retreated westward during an earlier erosion cycle. Perhaps the Long Hills surface is the only surviving remnant of a still older pediment. The lower terraces along Terlingua Creek probably represent slight local uplifts or lowerings of base level. They are of less magnitude and significance than the Long Hills and Green Valley pediment gravels, and they are not everywhere gravel covered.

Alluvium.—The material mapped as alluvium in the eastern part of the quadrangle is primarily valley-fill, much of which has probably been deposited as sheet-wash. The material is considerably less coarse than the igneous gravel, and its composition is principally that of the near-by sedimentary rocks. Undoubtedly it is of much more recent origin than the gravels at higher elevations to the west. That part of Hale Draw north of Dewees Tank (NE) is now dissecting a cream-brown alluvial fill, the upper 5 feet of which is fine-grained and fairly well bedded. The lower part contains a higher percentage of caliche and a greater number of Boquillas limestone pebbles than the upper 5 feet.

INTRUSIVE IGNEOUS ROCKS

Introduction

Lonsdale (1940) described the chief igneous masses in the southern part of the Agua Fria quadrangle and located them on a regional

reconnaissance map. Plate 1 shows more structural detail around the intrusive masses, and the following paragraphs supplement Lonsdale's work and the sections on igneous petrography and structure of this paper.

The hypabyssal intrusive igneous rocks of the Agua Fria quadrangle occur as ruptured laccoliths, stocklike bysmaliths (?), cores of trap-door domes, plugs, dikes, and sills. The rocks range in composition from soda rhyolites to picritic basalts and include an analcime-bearing series. Many of the intrusive masses are so closely interrelated with structure that to discuss the two independently is impractical. This is particularly true of the trap-door domes, which hold the key to the understanding of several of the more important intrusives.

Trap-door Domes

Trap-door domes are a combination of an unique igneous mode of occurrence and faulting. Knechtel (1944) describes domes with a central trap-door block as follows:

"The subordinate domes ... were formed by bodies of igneous rock which were punched upward into the sedimentary rocks. They range in diameter from 1½ to 3½ miles. Each is typically subcircular or subelliptical in plan and normally includes a hinged block that is raised on a nearly vertical fault of curved trace. The rock strata in such a block are tilted up like a trap-door which has opened along the fault and slopes down toward the opposite side of the block."

Gray Hill (SE) is the best example of this unusual structure in the Agua Fria quadrangle (Fig. 3). Here the uplifted, rectangular trap-door block, which is elongated in a northwest direction, dips to the northwest toward the hinge and is bounded on the other three sides by relatively straight faults that intersect almost at right angles. The two parallel faults are called paired faults, and the one fault at the southeast end, parallel to and opposite the hinge, is referred to as the unpaired fault. The latter has the greatest throw, and both paired faults decrease from a maximum throw at their intersection with the unpaired fault to zero at the hinge. Although no igneous rock is exposed at Gray Hill, a bysmalith-like intrusive mass is postulated to explain this special type of dome. Relationships between exposed igneous masses and other similar, though not so perfectly developed, trap-door domes support this assumption. Devils River, Grayson, Buda, and Boquillas crop out in the tilted trap-door block, but the flanks of the dome consist principally of Boquillas flags.

Red Bluff, a domical uplift along the east margin of the area, is similar to the domes described by Knechtel except that faulting, which must have occurred on the northwest flank, is obscured by the soda trachyte intrusion. The red bluff is a narrow crescent-shaped wall that terminates the dome to the northwest. The vertical wall, which resembles a ring-dike, towers 700 feet above the surrounding flat and stands 350 feet higher than the deroofed portion of the laccolithic intrusion. Presumably as the dome was being arched by the injection of viscous magma, its northwest flank fractured and an arcuate fault resulted. Being a line of weakness, the fault offered a means of escape for the magma, which, possibly aided by stoping, moved upward and thereby formed the mass that now stands as a towering semicircular wall after the previously enclosing sedimentary rocks were eroded. That part of the Boquillas roof rock nearest the concave or southeast side of the bluff has been stripped so that crude, vertical columnar jointing in the laccolith (?) proper is revealed, and Boquillas beds 40–50 feet above the igneous-sedimentary contact have been altered by the intrusion. Apparently the ruptured Red Bluff dome results from a partially deroofed laccolithic intrusion, and it strongly resembles a trap-door dome.

Panther Mountain (Pl. 2, fig. 3), a dome with highly faulted flanks, is not strictly a trap-door dome, but it evidently passed through such a stage at one time. Its only difference from a typical trap-door is the presence of an additional fault where the hinge-line should be. The north and west walls of this partially deroofed stocklike soda rhyolite mass are essentially vertical. The upper Devils River caps the southern portion of the intrusion and dips so steeply in a southerly direction that Grayson, Buda, and lower Boquillas flags are preserved only at the extreme south edge of the mountain. With Panther Mountain punched up through its center, the dome takes on the aspect of a stocklike bysmalith. The steep southward tilt of the block suggests that the upward-moving

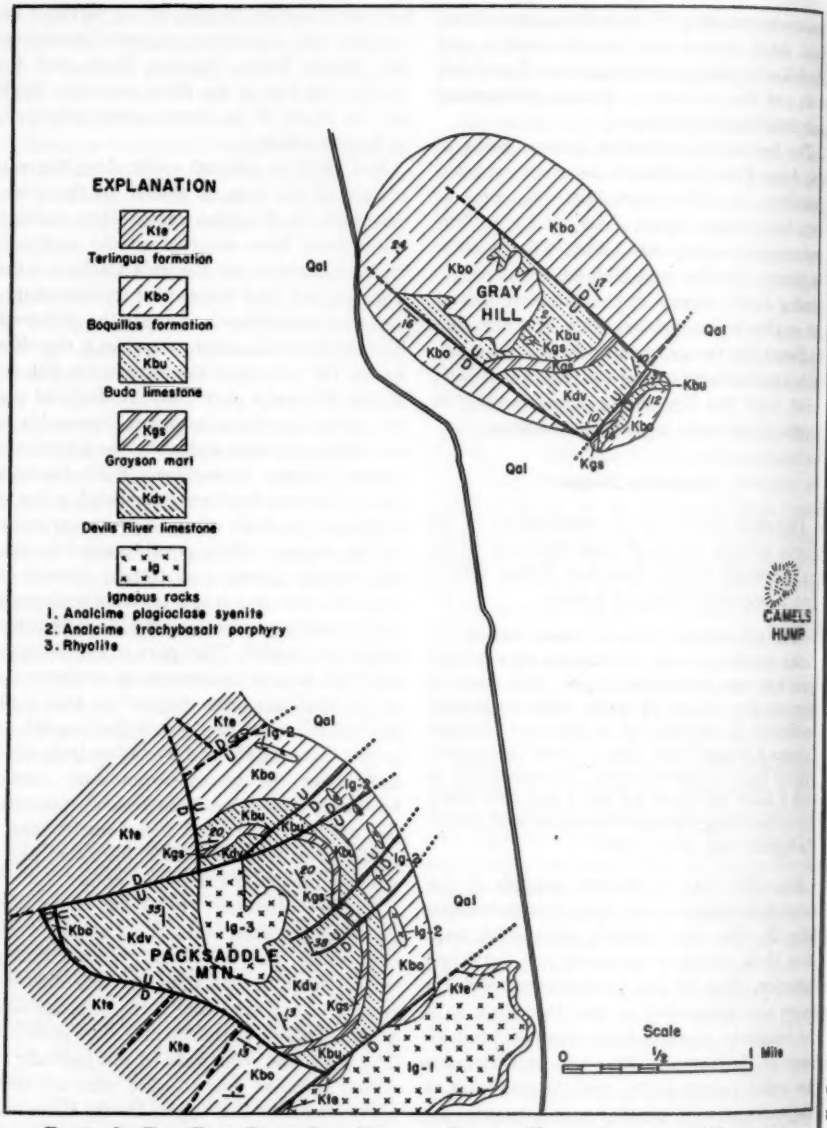


FIGURE 3.—TRAP-DOOR DOME, GRAY HILL, AND DOMICAL UPLIFT, PACKSADDLE MOUNTAIN

magma at first lifted only one end of the block and thereby formed a trap-door, but eventually the pressure became so great that the hinge-line also fractured and the entire block was lifted vertically, though differentially.

Stocks, Laccoliths, Bysmaliths, Plugs, Etc.

The largest single body of igneous rock in the quadrangle is the soda-rich rhyolite of Agua Fria Mountain, a stocklike mass which is about

2 miles in diameter and towers 1500 feet above the average level of the surrounding country. The walls of the mountain are so steep, vertical, or overhanging that they suggest the magma pierced the sediments in a very pasty or semi-solid state. Huge, irregular vertical columns of the reddish-weathered soda rhyolite stand as precipitous cliffs around the periphery of the mass. The most prominent overhanging cliff rises 350 feet above Agua Fria Spring, the water of which emerges from Aguja sandstone pulled up as a narrow fault block that fringes the west side of the mountain. The rhyolite top of the mountain weathers into plates that clink when walked upon.

Although Agua Fria Mountain consists of many peaks, all have practically the same elevation, which suggests that the stocklike mass was originally relatively flat-topped. Perhaps the peaks represent almost the highest elevation reached by the rhyolite. No sedimentary rocks are now present on top of the mountain, but comparison with structurally similar Panther Mountain to the east suggests that Devils River limestone was the roof rock.

Plate 1 indicates that Agua Fria Mountain, the center about which Tascotal Mesa fault and others curve, was instrumental in the development of structure in the south part of the quadrangle. Lonsdale (1940, p. 1555) classifies Agua Fria Mountain, along with similar masses, as a thick uncovered laccolith or bysmalith. The writer favors the idea of a bysmalith and postulates that the possible laccolithic portion of the mass extends to the northeast almost as far as Tascotal Mesa fault. If Agua Fria Mountain proper is only the stocklike portion of a more extensive igneous mass, then the entire structure is a bysmalith rather than a simple laccolith.

The contour map reveals a series of concentric rings of topographic highs and lows on top of Agua Fria Mountain that suggests a cylinder-and-piston effect or a telescopic manner of magmatic emplacement. This postulates that the outer shell cooled more rapidly, owing to contact with bed-rock, became more viscous and acted as a cylinder in which the hotter and more mobile interior piston could still move upward. The zone between the outer cylinder and the inner piston would, under these conditions, be subjected to considerable strain. Hence these rocks would be weakened, would erode more easily, and topographic lows would result. The ring of highest peaks around the periphery of the mountain corresponds to the postulated outer cylinder; the ring of topographic lows inside the peaks represents the rocks supposedly subjected to greatest stress, and the remaining central portion represents the piston.

Packsaddle Mountain is a complexly faulted dome in which an irregularly shaped quartz-poor rhyolite plug has punctured the roof. It is possibly a laccolith or bysmalith. Either the magma of the Packsaddle Mountain plug was differentiated into a core and an outer shell with an intervening transition zone, or the cylinder-piston or telescoping effect proposed for Agua Fria Mountain also operated here and resulted in three different phases of the rock on top of the plug. Most fresh specimens of the rhyolite are grayish-brown to pink, porphyritic, and exhibit swirls. Columnar jointing is well developed in the dense shell rock, which weathers to dark reddish-brown and commonly has a coat of desert varnish. The core rock exhibits excellent vertical and colored flow bands and weathers to huge light-brown boulders. The intermediate or transition zone is reddish and less dense than either the inner piston or outer cylinder. A fourth type of rock, a tightly cemented agglomerate or breccia that occurs as huge boulders in the saddle of the mountain, is probably a remnant of volcanics.

There are several pluglike masses in the southern part of the quadrangle, the most prominent of which are Camels Hump, Hill 4142, a black hill southwest of Packsaddle Mountain, Hill 4302, and possibly the circular mass just south of Agua Fria Mountain.

Bed-rock outcrops are poor around Camels Hump. Due to the rhyolite intrusion, which shows vertical flow structure, the Boquillas-Terlingua blocks exposed on the east side are badly broken. Effects of metamorphism appear to be slight, although some baked limestone is present in the saddle. Remnants of a basic sill, also intruded by the plug, cap basal Terlingua (?) beds and form a small discontinuous bench on the east flank of the hill.

The trachyte plug that forms Hill 4142 (SE) has intruded a down-dropped block of Aguja sandstone. The throat rock is porphyritic with glassy phenocrysts set in an aphanitic groundmass, has excellent flow structure, weathers to reddish-pink, and in many places exhibits a coat of desert varnish. An intrusion breccia occurs around its periphery, and well-developed columnar jointing is present on the southeast side of the hill.

The plug of picritic basalt that forms the small black hill southwest of Packsaddle Mountain has another set of joints normal to the well-developed columnar jointing. This causes the columns to break down into thin hexagonal plates. The fine-grained rock is heavy, dense, black, weathers rusty gray to reddish-brown, and contains visible olivine crystals.

Hill 4302 just south of Panther Mountain is a pluglike intrusion of soda rhyolite very similar in composition to that of Agua Fria Mountain. Huge columns form vertical cliffs, and a vertical parting, suggestive of flow structure, causes the rock to weather to thin plates that clink loudly when walked upon. The rock also shows concentric banding or swirl structures. The mass on the north flank of Hill 4302, which consists of fragments derived from the plug and tightly cemented with ferruginous cement, may be a Recent breccia. Another smaller mass just west of the hill is a tuffaceous breccia, possibly a remnant of the volcanic series.

Poor exposures around the base of the almost circular hill just south of Agua Fria Mountain make it difficult to determine whether this mass is a thick deroofed sill or a plug. In shape and development of massive columnar jointing, the intrusive resembles a plug; viewed from a distance, Terlingua beds appear to underlie the igneous rock. Thin horizontal plates weather from the upper surface of the mass and suggest horizontal flow structure, which evidence favors a sill. The dark-gray to black, heavy, dense, fine-grained rock has a reddish-brown weathering surface, and harder, lighter-colored elliptical pellets, up to 2 inches in maximum diameter, weather from the rock.

A small trachyandesite plug, half a mile southwest of Panther Mountain, occurs in a minor fault zone and consists of a badly brecciated mass of cream-gray to pink fragments cemented with ferruginous material. Calcite veins and small vugs are common. Perhaps the rock exposed is an intrusion breccia.

Sills

Several basic sills with a feeder dike are exposed in the 400-foot west canyon wall of Terlingua Creek a mile west of Panther Mountain; Hill 3450, which tops the cliff, was named Sill Hill. Another combination feeder dike and sill occurs just outside the southwest corner of the quadrangle. Locations of several more extensive sills, most of which are uncovered, and the formations in which they occur are:

Sills	*Formation*
Black Hill	Terlingua
Red Bluff	Boquillas
Pitahaya Hills	Aguja
Hill 3604 (SE)	Terlingua
Hill 3683 (SE)	Terlingua
Area southwest of Agua Fria Mountain	Terlingua

Dikes

The dikes in the western part of the quadrangle have a northwesterly trend which parallels that of the major structural features. Those of the central part of the quadrangle, however, are aligned in a northeasterly direction at right angles to structural trends. All dikes in the area are practically vertical, and none is more than a few feet thick. The longest dike, on Fizzle Flat, extends over 2 miles to the northeast. The highest dikes, those in Devils Graveyard (Pl. 4, fig. 1), stand 200–300 feet above the surrounding country.

Metamorphic Effects

The effects of contact metamorphism are relatively slight, even in the largest igneous occurrences. Noticeable effects on the enclosing country rock generally consist of no more than slight baking plus some color change a few feet from the igneous contact. Little, if any, mineralization of the country rock is apparent at most places.

Igneous Petrography

A number of igneous rocks in the southern part of Agua Fria quadrangle and in Brewster

County were described by Lonsdale (1940) and Lonsdale and Dickson (1948). Microscopic studies of additional rocks from the area by the writer are conveniently summarized in a paragraph from Lonsdale (1940, p. 1541):

"The igneous rocks include an analcite-bearing series and intermediate, trachytic, and rhyolitic types, most of which are soda-rich. The analcite-bearing types range from melanocratic gabbroid to syenitic types. Analcite is primary, deuteric, and hydrothermal and was formed through a rather long period. The complete assemblage is alkaline and resembles the suites from Spanish Peaks, Colorado, and other alkaline subprovinces along the front of the Rocky Mountains."

The petrography of the Agua Fria rocks is presented in Table 1. Lonsdale's (1940, p. 1601) special classification for the analcime-bearing rocks, which are such an important group in the Alpine-Terlingua area, adapted from Niggli (1931), is used. Grouping into families, such as microgabbros and basalts, on the basis of grain size is after Hatch and Wells (1937, p. 155, 201).

Structural Geology

General Description

Regional structure in the Big Bend establishes the local structural pattern of the Agua Fria quadrangle (Fig. 4). Approximately 10 miles northeast of the quadrangle are the Santiago Mountains, the northwest continuation of the Sierra del Carmen that lies some 30 miles to the east. This chain forms the easternmost front range of the Rocky Mountains in Texas. The northeast flank of the circular Solitario dome, structurally the highest part of the broad anticlinal Solitario uplift that extends southeastward to Terlingua, lies in the southwest corner of the quadrangle. Between these two positive elements, the Solitario to the southwest and the eastern front of the Rockies to the east and northeast, lies the Agua Fria quadrangle, which, as a whole, is structurally low, due principally to almost vertical normal faults.

Generally, the area is part of the great sunken block described by Udden (1907b) and Baker (1935a). According to Udden (1907b, p. 80-81), a part of the sunken block lies in that area bounded on the east by the front ranges of the Rocky Mountains, on the west by the Santa Elena fault scarp, on the south by the Rio Grande, and on the north by the igneous Corazones and Rosillos mountains, which lie east of and approximately at the same latitude as the south boundary of the Agua Fria quadrangle. The sunken block measures 39 miles from east to west, has dropped 4000–6000 feet structurally, and is extensively faulted and folded. Baker (1935a, p. 174) wrote: "Only exceptionally are the strata in the Big Bend sunken block horizontal. Dips more frequently are from 10° to 30°." Domes, laccoliths, and other intrusive masses are common in the sunken cblok.

Lonsdale (1940, p. 1543) stated that "to the northwest the settling decreases and ends with the Solitario uplift. . . ." The present detailed mapping shows, however, that a portion of, or an adjustment to, Udden's sunken block extends northwestward into the Agua Fria quadrangle and forms a constricted northwest-trending component of the tremendous negative structural unit. Possibly the sunken block dies out to the northwest within the Agua Fria quadrangle. On the other hand, although narrowed and restricted within the quadrangle, the change in fault trends suggests that the block continues on to the west and northwest in a wider belt outside the mapped area. Baker (1935b, p. 380) expressed the opinion that the Big Bend sunken block extends northward as far as the southern part of Green Valley (NW).

Lonsdale (1940, p. 1543) described the Sierra del Carmen as "a broad step-faulted domical uplift." Similar step faults prevail in the Agua Fria quadrangle, especially in its northeast half, where faults such as the Old Stage Stand, Hale Cabin, White Trail, and Cheosa Waterhole are each downthrown to the southwest and express themselves as prominent southwest-facing fault scarps with the huge fault blocks tilted gently to the northeast. Generally the faults are aligned in a northwesterly direction except in the vicinity of Agua Fria and Packsaddle Mountains, where intrusive masses have modified the trend of near-by faults.

Although no Palezoic rocks are exposed in the Agua Fria quadrangle, the older geosynclinal facies undoubtedly underlies the Cre-

FIGURE 4.—STRUCTURAL SETTING OF THE AGUA FRIA QUADRANGLE
Modified from Structural Map of Texas, 3rd edition, by Sellards and Hendricks (1946).

taceous rocks of the area. Highly folded, faulted, and even overthrust Paleozoics with a northeasterly trend are exposed in the Solitario dome, just beyond the southwest corner of the quadrangle, and in the southwest end of the Marathon uplift about 10 miles northeast of the quadrangle. An angular unconformity separates the Paleozoic and Cretaceous rocks in both areas. The projection of the Paleozoic trends indicates that the Cretaceous rocks o the Agua Fria quadrangle rest directly, bu with angular unconformity, on the Ouachit facies, and that the quadrangle probably mark the position of the buried Marathon geosyn cline. There is no structural evidence for th old Marathon geosyncline within the Agu Fria quadrangle, for the northwest structura trends in the surface rocks are at right angle

TABLE 1–PETROGRAPHY OF THE IGNEOUS ROCKS OF THE AGUA FRIA QUADRANGLE, TEXAS

LOCALITY	ROCK	OCCURRENCE	DIMENSIONS	TEXTURE	QUARTZ	FELDSPAR		PYROXENES	AMPHIBOLES	OLIVINE, SERPENTINE, IDDINGSITE	ORES	APATITE	OTHER MINERALS	REMARKS
						ALKALI	PLAGIOCLASE							
Camels Hump	Soda (?) rhyolite	Plug	Diameter: 1/4 mile	Fine-grained, subequigranular	Scattered grains (0.1± mm.)	Abundant laths and stubby xls. (0.1± mm.)					Altering to limonite		Trace zircon (?)	Reddish-brown alteratic material from riebeckite (?). Xls. set in feldspathic paste.
Packsaddle Mountain	Soda (?) rhyolite (quartz poor)	Plug	Diameter: 1/2 mile	Fine-grained, porphyritic (trachytic)	5% interstitial	88% anorthoclase phenocrysts (3 x 1 mm.) and groundmass laths (0.2± mm.)			Hornblende (?) xls., 1.2 x 0.35 mm., altering to limonite		7% ores. Magnetite grains; limonite.		Few zircon grains	Mode modified from Lonsdale (1940, p. 1567). Reddish-brown alteration material from amphibole(?) and/or pyroxene (?).
Panther Mountain	Soda rhyolite	Partially deroofed trap-door intrusive	Diameter: 1 mile	Fine-grained, porphyritic (subtrachytic)	Obscure in grd. mass. Rare corroded phenocrysts.	Anorthoclase phenocrysts (4± mm. long). Alkali laths 0.1± mm.		Trace aegirite-augite (?)	Little riebeckite (?)		Rare grains magnetite(?)	Few needles	Trace zircon. Titanite (?).	Apparent zoning in a few feldspar phenocrysts.
Hill 4302 (SC)	Paisanitic riebeckite soda rhyolite	Plug	Diameter: 1/2 mile	Fine-grained, subequigranular (imperfect granophyric)	Occult in groundmass	Anorthoclase laths and anhedral xls.			Small grains and few spongy riebeckite xls. up to 0.8 x 0.35 mm.		Rare magnetite grains up to 0.05 x 0.25 mm.		Few zircon xls.	Riebeckite pleochroic from dark blue-green to yellow-green, alters rusty brown.
Agua Fria Mountain	Paisanitic riebeckite soda rhyolite	Deroofed intrusive	Diameter: 2 miles	Fine-grained, porphyritic (granophyric groundmass)	Interstitial	Anorthoclase phenocrysts and groundmass		Aegirite-augite	Spongy riebeckite xls. and many scattered grains					Spongy riebeckite xls. poikilitic to anorthoclase and quartz. Riebeckite alters reddish-brown, strongly pleochroic, 5° to 7° extinction.
Hill 4142 (SE)	Soda (?) trachyte	Plug	Diameter: 1/4 mile	Fine-grained, porphyritic (imperfect trachytic)	Trace	Anorthoclase up to 1.7 x 0.8 mm. Alkali laths 0.13 x 0.05 mm.					Magnetite grains. Hematite and limonite.		Greenish micrallites	Reddish-brown material altered riebeckite (?).
Red Bluff	Soda trachyte	Ruptured, partially deroofed trap-door intrusive	1 x 1/2 mile	Fine-grained, subequigranular (good trachytic)	Practically quarts free	Pronounced orientation of alkali feldspar laths (0.3± mm.)		Aegirite-augite (bright green, 28° extinction)	Grains of rieb. and brownish sodic (?) hbl. Zoned xls. (0.35 x 0.15 mm.) of rieb. and arfved.(?)		Magnetite grains and skeleton xls. Limonitic material.			Sodic amphiboles markedly pleochroic, xl. ends fibrous and dark blue-green to black, maximum extinction 12°, fairly high relief.
Paint Mountain	Trachyte (vesicular)	Flows	Length: 1/4 mile Thickness: 30± feet	Very fine-grained, subequigranular (subtrachytic)		Abundant small laths (0.1 to 0.2 mm.)		Scattered augite grains			Few magnetite xls. (up to 0.7 mm.). Limonite from ore grains.	Minute stubby xls. associated with magnetite		Reddish-brown material suggests soda rich mafics. Possibly a soda trachyte. Two flows.
Hill 3605 (WC)	Plagioclase trachyte	Vertical dike	Length: 1 mile Width: few feet	Fine-grained, subequigranular	Little or none	Anorthoclase (2V=50°) xls. average 0.35 mm.	Small % of armored and indistinctly zoned sodic plagioclase		Few hornblende grains		Small xls. and grains of magnetite and ilmenite (?)	Needles notably developed		Numerous small vesicles. Few filled with calcite; few partially filled with clear to slightly clouded isotropic material.
In draw 1/4 mile SW of Hill 3963 (SW)	Andesine trachyte	Flow (lower)	Length: 2± miles Thickness: 25± feet	Fine-grained, porphyritic		Abundant laths 0.2 x 0.05 mm.	Armored andesine (An36-46) pheno. up to 1+ mm.	Considerable augite. One xl. 1 x 0.66 mm.		Some serpentine from augite	Magnetite up to 0.7 mm. has alkali feldspar inclusions. Limonite.	Stubby xls. up to 0.5 x 0.2 mm.		1± mm. ghosts of serpentine, calcite, and limonite. Alteration of plagioclase cores provides additional greenish material.
Dome just north of Hill 4142 (SE)	Trachy-andesite (?)	Sills	Diameter: 0.3 mile	Fine-grained, sparingly porphyritic	Little interstitial	Phenocrysts up to 2 mm. Groundmass laths and stubby xls.	Few andesine (An33) phenocrysts. Plagioclase groundmass laths.				Limonite patches, specks, and grains	Few xls. and many needles	Little leucoxene	Calcite: secondary and as alteration of feldspar. Rock badly weathered, possibly andesine trachyte.
Hill 3251 (SC)	Trachy-andesite (?) (brecciated and badly weathered)	Plug-like intrusive	Diameter: 0.15 mile	Fine-grained, porphyritic (trachytic)	ANALCIME	Few anorthoclase (med. 2V) pheno. Alkali laths and stubby xls. (0.3 x 0.2 mm.) in groundmass.	Rare phenocrysts up to 0.8 mm. Clear groundmass laths (n > 1.54).		BIOTITE				Calcite veins and cavity fill	Rock composed principally of feldspar. Some phenocrysts have glassy armor.
South flank of Hill 3903 (SW)	Trachy-andesite (?) (vesicular)	Flow (lower)	Length: 2± miles Thickness: 25± feet	Very fine-grained, porphyritic (subtrachytic)		Stubby to lath-shaped groundmass xls. (n < 1.54) 0.15± mm.	Thin alkali armor on zoned andesine (An45) phenocrysts (up to 2 mm.)	Trace augite		Iddingsite ghosts up to 0.7 mm.	Magnetite xls. up to 0.5 mm.	In phenocrysts and magnetite. Up to 2 mm. in groundmass.	Opal and tridymite amygdules	Pasty groundmass with feldspar laths, minute specks, needles, rods, and light yellow-green alteration material.
3/4 mile N 30 E of Camels Hump	Altered analcime plagioclase micro-syenite (?)	Uncovered sill	0.2 x 0.1 mile	Fine-grained, porphyritic	Interstitial, rudimentary ocellar, and replacement types. Turbid.	Phenocrysts and long laths. (Probably originally more abundant).	Large labradorite (An56) phenocrysts up to 8 mm. Zoned and armored laths.	Augite inclusions in phenocrysts. Purplish augite xls.	Small inclusions in phenocrysts. Plentiful in groundmass. Alters to greenish material.	Serpentine and olivine ghost xls. Spherulitic serpentine.	Magnetite and pyrite grains, ilmenite; limonite, leucoxene	Large, fat, stubby xls.		Highly analcitised rock. Suggests originally more potash feldspar. Greenish alteration material has peculiar reddish pleochroic color characteristic of sodic rocks.
South flank of Red Bluff	Altered analcime plagioclase syenite (?)	Sill	Length: 1+ mile	Medium-grained, porphyritic	As alteration product and replacement after feldspar	(Probably bulk of original feldspar was alkali)	Labradorite (An65) phenocrysts up to 2.5 mm. Armored laths.	Zoned, titaniferous (purplish) aug. xls., up to 2.5 mm., hosts to apatite and ores.	Long, thin, fresh shreds	Iddingsite and limonite ghosts, up to 2+ mm., after ol. (?). Serp. in groundmass.	Magnetite, pyrite, ilmenite; leucoxene	Small xls.	Spherulitic to fibrous zeolites	Deuteric alteration extensive. Practically indeterminate. Calcite in cavities.
South of Agua Fria Mountain	Altered analcime plagioclase micro-syenite (?)	Uncovered sill (?) or plug (?)	Diameter: 1/2 mile	Fine-grained, subequigranular	As deuteric product and cavity fill	Altered laths and subquadratic xls. more abundant than plagioclase	Altered laths show albite twinning	Microlites and crystallites of augite		Much light green serpentine material in groundmass	Magnetite grains and xls.	Small xls.	Little fibrous zeolite	Seriate xls. Deuteric action; rock appears fresh, but practically indeterminate. Calcite in cavities and alteration product.
Hill 3700 (SW)	Andesite	Dike	Length: 1 mile Width: few feet	Microporphyritic (subtrachytic)			Andesine (An35) laths, up to 0.3 mm., in feldspathic paste.				Magnetite xls. up to 0.2 mm. Limonite.		Minute perovskite (?) grains	Light colored pasty groundmass with iron ore specks and minute plagioclase needles. Calcite abundant (xls. up to 0.3 mm.).
Hill 3580 (SW)	Trachy-basalt	Plug	Diameter: 0.1 mile	Fine-grained, porphyritic		Anorthoclase phenocrysts, 0.7 x 0.6 mm., grid twinning. Alkali laths and stubby xls.	Alkali armored phenocrysts, zoned (An63 to An30), up to 2.2 x 1.3 mm. Seriate laths.				Magnetite grains and xls., ilmenite; limonite, leucoxene	Few small xls.	Calcite from calcic feldspar and in vesicles	Microperthitic. Excellently zoned and armored feldspar.

TABLE 1– PETROGRAPHY OF THE IGNEOUS ROCKS OF THE AGUA FRIA QUADRANGLE, TEXAS (CONT'D)

LOCALITY	ROCK	OCCURRENCE	DIMENSIONS	TEXTURE	ANALCIME	FELDSPAR		PYROXENES
						ALKALI	PLAGIOCLASE	
Dome just north of Hill 4142 (SE)	Analcime trachybasalt porphyry (badly weathered)	Sill	Diameter: 0.3 mile	Fine-grained, porphyritic	As cavity fillings and replacement type	Xls., armor, and in groundmass	Zoned and armored An64 phenocrysts up to 3.5 mm. Groundmass laths.	
North Pitahaya Hill	Analcimitic trachy-dolerite	Uncovered sill	Numerous small isolated exposures	Fine- to medium-grained, seriate (ophitic)	Little primary and interstitial	Considerable amount	Labradorite	Purplish augite xls. up to 1.5 mm.
Hill 3604 (SE)	Analcime trachybasalt porphyry	Uncovered sill	1 x 0.5 mile	Fine-grained, porphyritic	Turbid to clear interstitial, replacement, and cavity fill	Few phenocrysts and as groundmass xls.	Zoned and armored An60 phenocrysts up to 7 mm. Plagioclase laths in groundmass.	Purplish augite xls. Some with hour glass structure.
Hill 3683 (SE)	Analcime syeno-gabbro (?) porphyry	Uncovered sill	1.5 x 0.5 mile	Fine- to medium-grained, porphyritic	Cloudy to clear interstitial and replacement	Relatively high % anorthoclase. Alkali groundmass laths average 0.3 mm.	Zoned and armored lab. pheno. av. 1 x 1.5 mm. and partly replaced by analcime. Plag. laths average 0.3 mm.	Gray to purplish subhedral augite xls.
Terlingua Creek 0.3 mile west of Panther Mountain	Analcime micro-syenogabbro (?) (badly altered)	Sill	Exposed in canyon wall for 1/4 mile. Up to 50 feet thick.	Fine- to medium-grained, subequigranular	Clear to turbid interstitial patches up to 1.3 mm.	Perhaps equal in % to plagioclase	Armored An60 xls. up to 1.5 mm. Bundles of smaller laths.	Titaniferous augite
1-1/2 miles due north of Pack-saddle Mountain	Analcime trachy-basalt (?) porphyry	Uncovered sill	Diameter: 0.1 mile	Fine-grained, porphyritic	Turbid. Interstitial, replacement, ocellar.	Groundmass laths. Stubby xls. Armor on plagioclase.	Zoned and armored labradorite phenocrysts up to 8 mm. Alkali rims on plagioclase laths.	Purplish, twinned augite xls. up to 2 mm. Small xls. in groundmass.
Black Hill	Analcime basalt porphyry	Sills	Diameter: 0.15 mile	Fine-grained, porphyritic	Interstitial, replacement, and vesicle fill.	Few groundmass laths.	Zoned and armored An62 pheno., up to 4.5 mm., poikilitic to augite, magnetite, and olivine. Plag. groundmass laths.	Augite grains and small xls.
Hill 3550 (SE)	Analcime basalt	Uncovered sill	0.5 x 0.1 mile	Fine-grained, subequigranular (trachytic and ophitic)	Clear, primary, interstitial	Few xls. up to 0.5 x 0.4 mm.	Abundant laths, zoned An53 to An40	Augite xls. hosts to plagioclase
Fizzle Flat	Chilled basalt	Dike	Length: 2.2 miles Width: 10 to 12 feet	Exceedingly fine-grained with few plagioclase xls. (subtrachytic)		Slight alkali armor on plagioclase	Seriate zoned and armored An65 laths up to 1.5 mm. Poikilitic to olivine and magnetite grains.	Minute augite grains
Hill 3494 (SC)	Analcimitic diabasic microgabbro	Flow (?)	Diameter: 0.2 mile Thickness: 20± feet	Fine- to medium-grained, seriate (ophitic)	Little interstitial and as alteration of plagioclase	Little as rims and crude perthitic intergrowth	Slightly zoned and armored An63 to An55 xls., up to 1.2 mm., with minute inclusions. Slender laths (0.2± mm.).	Faint purplish augite xls. up to 1.8 mm.
South flank of Hill 3903 (SW)	Analcimitic diabasic microgabbro	Flow (upper)	Length: 2? miles Thickness: 25± feet	Fine- to medium-grained, subequigranular (ophitic)		Very little	Lath shaped An67 xls. up to 2 mm. Abundant plagioclase laths.	Aug. grains and xls., up to 2 mm., hosts to lab. and iddingsite
Black ridge 1-1/2 miles SW of Agua Fria Mt.	Analcime basalt porphyry	Uncovered sill	1/2 x 1/2 mile within quadrangle (extends beyond map)	Fine-grained, porphyritic	Interstitial	Little as thin armor on large plagioclase phenocrysts	Very large, clear, An60 phenocrysts. Plagioclase groundmass laths, 0.3 to 0.4 mm.	Small augite xls.
Hill 3580 (SW)	Olivine basalt porphyry	Dike	Length: 0.1 mile Width: 1 to 2 feet	Fine-grained, porphyritic		Little as rim on plagioclase feldspar	Slightly zoned and thinly armored An60 phenocrysts, up to 2 mm., poikilitic to magnetite, olivine, and augite grains. Seriate plagioclase laths.	Small augite xls. and microlites (?)
Black Hill 1 mile SW of Pack-saddle Mt.	Picritic basalt	Plug	Diameter: 0.2 mile	Fine- to medium-grained, seriate	Trace (?)	Practically none	Minute An64 laths in paste	Abundant gray, zoned augite xls. up to 1.5 mm.
Terlingua Creek 0.3 mile west of Panther Mountain	Analcime alkali basalt	Sill (upper)	Length: 1/4+ mile Thickness: 15 to 20 feet	Fine- to medium-grained, seriate	Clouded, plentiful in groundmass	Possibly little originally present in groundmass, but highly altered	Very small (labradorite?) laths, up to 0.5 mm.	Abundant zoned, twinned, and hour glass euhedral augite xls. up to 1 mm.

BIOTITE	OLIVINE, SERPENTINE, IDDINGSITE	ORES	APATITE	OTHER MINERALS	REMARKS
Minute inclusions in plagioclase	Antigorite (?) after olivine (?). Serpentine material in groundmass.	Magnetite grains, rare ilmenite; limonite, leucoxene	Fat, stubby xls. in clots with altered mafics	Calcite after more calcic plagioclase	Serpentine, calcite, and analcime as alteration products.
	Olivine xls., up to 1 mm., hosts to feldspar laths	Magnetite grains and xls.	Few xls.		Seriate grain size. Specimen fresh.
Flakes	Serpentine-olivine xls. up to 2 mm. Serpentine in groundmass.	Magnetite grains. Ilmenite-leucoxene, up to 0.5 mm.	Xls. up to 1 mm. long	Sperulitic zeolites as alteration of feldspar	Strikingly porphyritic. Groundmass xls. average 0.1 to 0.2 mm.
Rare flakes	Serpentine from olivine	Magnetite grains and small xls. Trace pyrite.	Numerous needles	Chlorite. Little calcite.	Clusters of serpentine, olivine, magnetite, and augite.
Rare flakes	Serpentine ghosts after olivine. Serpentine (?) in groundmass.	Pyrite and magnetite grains and small xls.	Needles and small xls.	Sperulitic zeolites	Much deuteric alteration of minerals to serpentine, analcime, and zeolites. Exact classification indeterminate.
Flakes outline analcime ocelli	Serpentine-olivine xls., up to 1.7 mm., hosts to apatite. Serp. in groundmass	Magnetite and pyrite. Ilmenite-leucoxene.	Fat, stubby xls. and irregular shapes	Fibrous zeolites. Little calcite.	Highly altered. Probably more plagioclase than alkali feldspar. Some completely altered plagioclase cores have fresh alkali rims.
	Olivine xls., up to 1.3 mm., serpentine along cracks. Both in groundmass.	Magnetite grains and small xls.	Small elongate xls.	Fibrous to spherulitic zeolites	Plagioclase rich rock. Clots of fine-grained augite and ore grains in feldspathic paste. Amygdules of calcite, analcime, and zeolites.
	Olivine (0.5 to 1 mm.)	Magnetite grains and xls. up to 0.7 mm.		Calcite as cavity material	Seriate mafics show lineation. Plagioclase laths in bundles. Fresh specimen.
	Olivine grains and xls. up to 0.6 mm.	Unusually abundant minute magnetite grains			Super chilled rock. Feldspathic paste with minute laths and grains of plagioclase, magnetite, olivine, and augite. Aphanitic hand specimen.
Small wisps	Numerous small slightly serpentinized olivine xls.	Magnetite grains, xls., and small inclusions in feldspar			Some alignment of feldspar laths.
	Olivine xls., up to 2 mm., alter to iddingsite	Small grains and rods of magnetite (?)		Calcite fills vesicles and cracks	Thin section fresh; hand specimen appears badly weathered.
	Slightly serpentinized olivine grains and xls. up to 0.8 mm. Also in groundmass.	Magnetite grains			Seriate grain size in groundmass. Clear labradorite phenocrysts, 2± inches long. Chilled rock.
Rare minute flakes	Euhedral olivine xls., up to 0.8 mm., serpentine along cracks. Olivine in groundmass.	Magnetite grains			Pasty groundmass with laths and stubby plagioclase, minute ore and olivine grains. Seriate iron rich olivine is biaxial negative. Chilled rock.
Few wisps	Abundant olivine up to 1.5 mm. with serpentine along cracks	Scattered magnetite grains	Trace		Pasty groundmass. Rock is feldspar poor. See Lonsdale (1940, No. XX of Table 17) for chemical analysis.
Flakes up to 0.5 mm. long	Abundant serpentine-olivine xls. up to 1.5 mm. long	Magnetite grains	Present	Fibrous and spherulitic zeolites	Low % clouded, pasty, feldspathic groundmass; zeolitized feldspar probably labradorite; biotite indicates alkaline affinity of mafic rich rock; secondary calcite.

to the no
surface Pa

Both fe
the Big B
are the n
the Agua
uplifts, s
trap-door
than simp
ing struct
occur in
parallel f
vening fa
and rift
grabens a
the extre
and the
and Tert
is a part.
The tre
except in
where the
ample, cl
This dec
Mountain
Solitario
tremendo
The t
amounts
many is
(Table 2
few exce
are progr
Cheosa
a fault z
of Terlin
tively sh
into sliv
faults of
The n
Ridge (
west are
the same
direction
the fault
northwes
tion con
direction
block th

to the northeast structural trends of the subsurface Paleozoic rocks.

Normal Faults

Both folding and faulting are widespread in the Big Bend sunken block, but normal faults are the most important structural element in the Agua Fria quadrangle. Even in domical uplifts, such as Packsaddle Mountain, and in trap-doors, such as Gray Hill, faulting rather than simple folding chiefly governs the resulting structure (Fig. 3). Many faults in the area occur in pairs, and two faults may extend parallel for miles. More of the narrow intervening fault blocks are grabens than horsts, and rift valleys are not uncommon. Notable grabens are the rift valley in the Boquillas in the extreme northeast corner of the quadrangle and the block composed of Gulf Cretaceous and Tertiary strata of which Paint Mountain is a part.

The trend of the major faults is northwesterly except in the southern part of the quadrangle, where the strike of Tascotal Mesa fault, for example, changes from northwest to due west. This decided change indicates that Panther Mountain, Agua Fria Mountain, and the Solitario have influenced structural conditions tremendously in this part of the quadrangle.

The throw of most of the major faults amounts to hundreds of feet, and the trace of many is marked by a prominent fault scarp (Table 2). From northeast to southwest, with few exceptions, the northwest-trending faults are progressively downthrown to the southwest.

Cheosa Waterhole fault is, more specifically, a fault zone; the faulting, especially northwest of Terlingua Creek, consists of numerous relatively short echelon faults that cut the rocks into slivers. This fault zone, like many other faults of the area, dies out to the northwest.

The normal faults that bound the Riddle Ridge (C) horst on the northeast and southwest are practically vertical, and apparently the same two faults continue in a northwesterly direction under a gravel cover (Pl. 1). If so, the faults are pivotal, for the vertical movement northwest of the supposed axis of rotation (position concealed by gravel) is in the opposite direction to that southeast of it. Thus the block that is a horst at its narrow southeast end widens and develops into a graben to the northwest.

Hill 3564, southwest of Packsaddle Mountain, is a significant horst, because the telescopic structural effect described in the discussion of Agua Fria Mountain is well developed in the Boquillas flags in this hill. Perhaps an uncovered igneous intrusive is responsible for this type of structure, in which a concentric fault pattern develops with beds nearer the structural center of the hill pushed progressively higher than those nearer the periphery.

TABLE 2.—ESTIMATED STRATIGRAPHIC THROW OF SEVERAL MAJOR FAULTS

Fault	Position	Approximate throw in feet
Old Stage Stand	Old Stage Stand	500
Hale Cabin	Alpine-Terlingua road	500
Cheosa Waterhole	Alpine-Terlingua road	800
Fizzle Flat	Clanton-Agua Fria ranch road	500
Tascotal Mesa	Paint Mountain	1000±
Solitario	Hill 3903	2200±

Many of the faults at Packsaddle Mountain and Agua Fria Mountain are at right angles to the general northwesterly structural trend of the area. These local faults, several of which are radial, probably resulted directly from the intrusions. A narrow fault block of Aguja sandstone fringes the west escarpment of Agua Fria Mountain, and a small block of Boquillas limestone on the north side of the mountain has also been elevated by the intrusion.

AGE OF THE FAULTING: Most faulting in the Agua Fria quadrangle occurred in Tertiary time, possibly fairly late, because the Buck Hill volcanic series is involved. The local radial faults associated with plug and stock-like masses probably originated at the time the Tertiary igneous rocks were intruded. Tascotal Mesa fault probably is younger than or contemporaneous with the Agua Fria intrusion, because that igneous mass definitely controls the fault pattern of the area surrounding it.

Part of the fault pattern in the Agua Fria quadrangle may have been established during the Laramide revolution at the close of Cre-

taceous time, so that renewed movements occurred along the existing fault zones during Tertiary time. Evidence for this conclusion is found at Hill B.M. 3540 and Hill 3546 in the central part of the quadrangle, less than 1½ miles apart. Hill B.M. 3540 lies slightly northeast of the Cheosa Waterhole fault zone, and Hill 3546 is within the zone. Both hills are capped by seemingly correlative Tertiary limestones. That at Hill B.M. 3540 rests on beds of the Fizzle Flat lentil, but between the base of the limestone at Hill 3546 and the top of the Fizzle Flat lentil are 83 feet of tuffaceous material, 16 feet of basal Tertiary conglomerate, and 57 feet of medium gray Terlingua (?) beds. At least 156 feet more section is preserved under the limestone on the downthrown side of the fault than on the upthrown. This suggests that Hill B.M. 3540 either stood so high that the members of the Buck Hill volcanic series older than the limestone cap were never deposited on it, or else they were deposited and subsequently eroded so that the fresh-water limestone was deposited on the Fizzle Flat lentil. In either event, sufficient displacement had already taken place prior to the deposition of the Tertiary limestone to preserve an additional 156 feet of sediments on the downthrown side of the fault. Perhaps at this particular place the faulting was a slow but continuous process that lasted from Laramide time to post-fresh-water limestone time, because the Tertiary limestone at Hill 3546 has been folded and distorted by faulting, even though it still maintains essentially the same elevation as the limestone at Hill B.M. 3540.

Domes

Folding is expressed appreciably in the quadrangle only in highly faulted domes. The best trap-door dome is Gray Hill. Other possible trap-doors or domes similar to them include Red Bluff and Panther Mountain. The Solitario and the small patch of Boquillas flags just east of the Alpine-Terlingua road at the south boundary of the area are typical domes. Hill 3564 southwest of Packsaddle Mountain is a dome-like uplift with a ground plan the shape of a flat-iron and with concentric faults that operated in a telescopic manner. Half Dome (SC) and the area just west of north Pitaha[y] Hill are domes that have been cut in half b[y] faulting. Fizzle Flat and the area northeast [of] the intersection of Hale Cabin fault and th[e] Alpine-Terlingua road might be included in [a] similar category. These very broad upwarp[s] the axes of which plunge gently to the northeas[t] and are at right angles to the faults, form ver[y] broad half-dome structural features. A test we[ll] for oil drilled at the crest (just east of th[e] road) of the gently arched upthrown fault bloc[k] northeast of the Hale Cabin fault was dry an[d] abandoned.

Geologic History

Late in Paleozoic time, the dominantly clastic sediments of the Marathon geosyncline were buckled, folded, and overthrust to the northwest. This diastrophism established the prevailing northeast trends in the Marathon and Solitario areas and obliterated the Paleozoic geosyncline. From late Paleozoic to early Cretaceous time the area stood above sea level and was eroded. Exposures in a deep and narrow canyon on the east flank of the Solitario reveal that, when the earliest Cretaceous seas advanced into the area, the Trinity sandstone and conglomerate were deposited on the beveled edges of highly inclined Paleozoic strata. Then, in sequence, follow several hundred feet of Glen Rose limestone, a few tens of feet of Maxon sandstone, several hundred feet of Devils River limestone, the Grayson, Buda, and Boquillas.

All Cretaceous sedimentary rocks within the quadrangle, with the possible exception of a small amount of Aguja, are marine. Adkins (1933, p. 505–508) points out that some of the upper Aguja beds are nonmarine, but few, if any, of the younger Aguja beds are preserved in the area. If the Tornillo clay, which is well developed farther south, was ever deposited in the Agua Fria quadrangle, it was removed by erosion during and following the Laramide revolution.

Most of the faulting occurred after the deposition of the Buck Hill volcanic series, for these strata are cut by faults. If a fault system developed in late Cretaceous time, presumably the late Tertiary faulting recurred along these

older lines of weakness. The angular unconformity which separates the basal Tertiary conglomerate from the east-dipping Comanche and Gulf Cretaceous formations on the northeast flank of the Solitario indicates that this structure, although not in its present form, became a positive element during the Laramide revolution.

Because the Santiago Mountains to the northeast also originated during the Laramide revolution, the Agua Fria area has probably been structurally negative since the close of Cretaceous time.

The erosion that resulted from the regional Laramide uplift removed all strata down to the Fizzle Flat lentil in the northern part of the Agua Fria quadrangle, but the section up through the lower Aguja beds is preserved in the south. Therefore, the basal Tertiary conglomerate, because of the widespread angular unconformity, rests on the beveled edges of progressively younger Cretaceous strata from north to south within the quadrangle. In the adjoining Buck Hill quadrangle to the north, the conglomerate rests on the Boquillas flags; and, according to Goldich and Elms (1949, p. 1173): "The persistence of the basal Tertiary conglomerate suggests that a similar break might be expected between the Tornillo formation, if it is of Cretaceous age, and the Chisos beds in the Chisos Mountains area." Apparently Udden's sunken block has exerted a dominant regional influence on erosion, deposition, and preservation of strata in the Big Bend area during Tertiary time.

The basal conglomerate of the Pruett consists principally of well-rounded pebbles and cobbles of Comanche limestones. Chert is also a constituent, and more angular materials were derived locally from underlying Cretaceous formations. The lack of igneous pebbles and cobbles in the conglomerate suggests either that igneous activity in the area had not commenced at the time the conglomerate was laid down or that the igneous rocks had not yet been exposed to erosion. The appearance of igneous pebbles and cobbles in younger breccias and conglomerates of the Buck Hill volcanic series indicate that an igneous source was supplying materials by the time these beds were deposited.

Goldich and Elms (1949, p. 1173–1175) have presented a detailed account of the history of the Buck Hill volcanic series which applies also to the Agua Fria quadrangle. The following points have been abstracted from that reference.

(1) Several widely spaced localities exhibit the regional angular unconformity between Cretaceous strata and the Tertiary volcanics.

(2) The Pruett is tentatively assigned to the Eocene on the basis of fossil gastropods in the fresh-water limestones, and the Duff formation is tentatively assigned to the Oligocene.

(3) Tertiary deposition probably was not continuous; undoubtedly materials were reworked and locally removed by streams. Breaks in the tuffs can escape detection because of the nature of the materials.

(4) Stratification of the tuffs and fresh-water limestones indicate that much of the Pruett was probably deposited in large temporary and shallow lakes.

(5) The high $CaCO_3$ content of the lower part of the Pruett suggests a mechanical derivation from exposed Cretaceous rocks, but some of the thick limestone sequences were precipitated. Algal structures and charophytes suggest an organic origin for much of the limestone.

(6) The source of the volcanic ash is problematical. The finer material could have come from great distances, but the breccia-conglomerates probably were derived from near-by sources.

(7) The intrusions, although all may not be of the same age, antedate the late faulting and indicate activity in late Tertiary time. In the southwestern part of the Jordan Gap quadrangle, igneous plugs intruded the younger Tascotal tuff beds. (Perhaps it was also at this time that a laccolithic intrusion raised the Solitario dome like a huge blister, which became the crest of the more extensive Solitario uplift.)

(8) The time of folding and faulting of the Buck Hill volcanic series is at least late Tertiary and is older than the basin fill and alluvial deposits of the region.

(9) Since the late Tertiary uplift, erosion has removed a great thickness of the volcanic series, forming Green Valley and again exposing the Cretaceous strata. Terraces (west of Terlingua Creek near Clanton ranch) and alluvial deposits indicate that the process has been

controlled by temporary base levels, and the present active downcutting indicates recent rejuvenation.

Economic Geology

Several structures that would make excellent oil traps are present in the Agua Fria quadrangle, but all tests for petroleum in the area have been unsuccessful. The Tertiary igneous rocks have intruded the sediments which would be the potential reservoir rocks, thereby decreasing porosity and permeability in some cases. Thermal effects would tend to destroy any hydrocarbons that may have been present when the domes were formed.

Copper prospects in the Solitario are reported by Baker (1935b, p. 412), and traces of native copper were found in the Boquillas flags on the northeast flank of the Solitario. But copper in commercial quantities probably does not occur in the Agua Fria quadrangle.

The same can be said of hematite, a few loose specimens of which were found on the northeast flank of Packsaddle Mountain. These are probably erosional remnants from the Aguja sandstone.

In this semidesert country which is devoted exclusively to ranching, water is by far the most important economic mineral. Agua Fria Spring, the most dependable and best supply of water in the quadrangle, is literally an oasis in the desert. Its output, apparently dependent upon the amount of rainfall received during the preceding year, fluctuates somewhat from year to year, but the spring has never run dry. There are several permanent water-holes and short stretches along Terlingua Creek, the greater extent of which is intermittent, and relatively shallow water wells dug near the creek are usually successful. Water in the northeast portion of the quadrangle is very scarce and must be pumped there through pipe-lines from Terlingua Creek and other sources. The area as a whole relies for its water for stock on surface run-off that collects in earthen tanks during and after cloudbursts, which are fairly common during the summer months.

Mansfield and Boardman (1932, p. 55–57) reported a nitrate deposit "without commercial possibilities" at Agua Fria Spring. The mineral from the deposit were described by Lonsdale (1926) as niter and soda niter.

References Cited

Adkins, W. S. (1933) *The Mesozoic systems in Texas*, Pt. 2, *The geology of Texas*, vol. I, *Stratigraphy*, Univ. Texas, Bull. 3232, p. 239–518.

Baker, C. L. (1935a) *Major structural features of Trans-Pecos Texas*, Pt. 2, *The geology of Texas*, vol. II, *Structural and economic geology*, Univ. Texas, Bull. 3401, p. 137–214.

——*et al.* (1935b) *Economic geology of Texas*, Pt. 1, *The geology of Texas*, vol. II, *Structural and economic geology*, Univ. Texas, Bull. 3401, p. 215–884.

Cragin, F. W. (1894) *The Choctaw and Grayson terranes of the Arietina* [Texas], Colo. College Studies, vol. 5, p. 40–48.

Eifler, G. K., Jr. (1943) *Geology of the Santiago Peak quadrangle, Texas*, Geol. Soc. Am., Bull. vol. 54, p. 1613–1644.

Fenner, C. N. (1948) *Incandescent tuff flows in southern Peru*, Geol. Soc. Am., Bull., vol. 59, p. 879–893.

Goldich, S. S., and Elms, M. A. (1949) *Stratigraphy and petrology of the Buck Hill quadrangle, Texas*, Geol. Soc. Am., Bull. vol. 60, p. 1133–1182.

—— and Seward, C. L. (1948) *Green Valley-Paradise Valley field trip*, West Texas Geol. Soc. guide-book, p. 10–36.

Hatch, F. H., and Wells, A. K. (1937) *The petrology of the igneous rocks*, 9th ed., George Allen & Unwin Ltd., London, 368 pages.

Henderson, Junius (1935) *Fossil non-marine Mollusca of North America*, Geol. Soc. Am., Special Paper 3, 313 pages.

Hill, R. T. (1900) *Physical geography of the Texas region*, U. S. Geol. Survey, Topog. Atlas, Folio 3, p. 1–12.

—— and Vaughan, T. W. (1898) *Geology of the Edwards Plateau nand Rio Grande Plain adjacent to Austin and San Antonio, Texas*, U. S. Geol. Survey, Ann. Rept. 18, pt. 2, 193–321.

Huffington, R. M. (1943) *Geology of the Northern Quitman Mountains, Trans-Pecos Texas*, Geol. Soc. Am., Bull., vol. 54, p. 987–1046.

Knechtel, M. M. (1944) *Oil and gas possibilities of the plains adjacent to the Little Rocky Mountains, Montana*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. Map 4.

Lonsdale, J. T. (1926) *Niter and soda niter from Brewster County, Texas*, Am. Mineral., vol. 11, p. 189–190.

—— (1940) *Igneous rocks of the Terlingua-Solitario region, Texas*, Geol. Soc. Am., Bull., vol. 51, p. 1539–1626.

—— and Dickson, K. O. (1948) *Analcime suite of igneous rocks, Brewster County, Texas* (Abstract), Geol. Soc. Am., Bull., vol. 59, p. 1337.

Mansfield, G. R., and Boardman, Leona (1932) *Nitrate deposits of the United States*, U. S. Geol. Survey, Bull 838, 107 p.

—— and Ross. C. S. (1935) *Welded rhyolitic tuff*

in southeastern Idaho, Am. Geophys. Union, Tr., p. 308–321.

Niggli, P. (1931) *Die quantitative mineralogische klassification der eruptivgesteine*, Schweiz. Min. Pet. Mitt., Bd. XI, Heft 2, p. 296–364.

Scott, G. (1926) *Études stratigraphiques et paléontologiques sur les terrains crétacés du Texas*, Université de Grenoble, Dr. Nat. Sci. Thesis.

Stephenson, L. W. (1948) *Notes on the stratigraphy of the Upper Cretaceous formations of the Big Bend area, Texas*, Bur. Econ. Geol., Univ. Texas, Unpublished.

Udden, J. A. (1907a) *Report on a geological survey of the lands belonging to the New York and Texas Land Company, Ltd., in the Upper Rio Grande embayment in Texas*, Augustana Lib. Pub., no. 6, p. 51–107.

Udden, J. A. (1907b) *A sketch of the geology of the Chisos country, Brewster County, Texas*, Univ. Texas, Bull. 93, 101 p.

Vaughan, T. W. (1900) *Reconnaissance in the Rio Grande coal fields of Texas*, U. S. Geol. Survey, Bull. 164, p. 1–88.

HUMBLE OIL & REFINING CO., WICHITA FALLS, TEXAS.

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY,

PUBLISHED WITH PERMISSION OF THE DIRECTOR OF THE BUREAU OF ECONOMIC GEOLOGY, THE UNIVERSITY OF TEXAS.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 64, PP. 197-234 FEBRUARY 1953

BIBLIOGRAPHY AND INDEX OF LITERATURE ON URANIUM AND THORIUM AND RADIOACTIVE OCCURRENCES IN THE UNITED STATES

PART 1: ARIZONA, NEVADA, AND NEW MEXICO

BY MARGARET COOPER

CONTENTS

	Page
1. Foreword	197
2. Bibliography	197
3. Index I. Gazetteer for Arizona, Nevada, and New Mexico	205
4. Index II. Geographical index for Arizona, Nevada, and New Mexico	208
5. Index III. Subject index for Arizona, Nevada, and New Mexico	222

FOREWORD

The following bibliography consists of references to published literature, press releases, speeches, and both open-file and other unclassified reports dealing with uranium, thorium, and other radioactive occurrences in Arizona, Nevada, and New Mexico. It represents the first section of a comprehensive bibliography planned to cover references to all similar deposits throughout the world. While the object has been to make the present bibliography as all-inclusive as possible, from the point of view of including all the major papers and at least one reference to each known radioactive occurrence in these States, only references for which the original text was readily available for examination and checking have been cited. The remaining old and new references will be added to this basic list when the section is ready for inclusion in the comprehensive volumes, planned for future publication as a complete bibliography of the entire United States and the world.

The main bibliography consists of an author section, in which each reference has been assigned an individual item number. Following the author listings are the anonymous notes, which are listed in chronological order, and alphabetically by title within each year. The bibliography proper is followed by three indexes: Index I, Gazetteer for Arizona, Nevada, and New Mexico; Index II, Geographical Index for Arizona, Nevada, and New Mexico; Index III, Subject Index for Arizona, Nevada, and New Mexico. The geographical and subject indexes have been made as detailed as practicable since the main reference entries have not been annotated. Where there are variations in spelling or alternate names for the same locality, a standard form has been used in the geographical and subject indexes, and the variations have been noted in the gazetteer. Where county boundary lines have been changed since a reference was written, the locality has been listed under the county in which it is found today.

A fairly extensive survey has been made of the geological and mining literature published through 1949 in compiling the references included in this bibliography. A few of the standard American and English geological and mining publications have also been reviewed upon the early part of 1952. Every reference cited in the bibliography has been checked with the original text.

BIBLIOGRAPHY

ALLEN, Milton Arthur
1. (and BUTLER, Gurdon Montague) Vanadium.
Arizona State Bureau of Mines, TUCSON, Mineral Technology Series No. 26, Bulletin, No. 115, 1921, 23 pp.
(See also BUTLER, Gurdon Montague, 7)

ANTHONY, John W.
2. Radioactive Uranium and Thorium.
Arizona Bureau of Mines, TUCSON, Circular, No. 13, 1948, 22 pp.

AXELROD, Joseph Meyer
3. (and GRIMALDI, Frank Saverio; MILTON, Charles; MURATA, Kiguma Jack) The Uranium Mineralization from the Hillside Mine, Yavapai County, Arizona.
American Mineralogist, MENASHA, Vol. 36, 1951, pp. 1–22.

BATES, Robert Latimer
4. (and BURKS, Marian R.) Geologic Literature of New Mexico through 1944.
New Mexico School of Mines, State Bureau of Mines and Mineral Resources, SOCORRO, Bulletin, No. 22, 1945, 144 pp.

Includes references to uranium and thorium occurrences in New Mexico.

BAUER, Herman L., Jr. See GRANGER, H. C., 28; STAATZ, Mortimer Hay, 85; WILMARTH, V. R., 95.

BERONI, Ernest P. See GOTT, Garland B., 27.

BUEHRER, T. F.
5. The Radioactivity of the Thermal Waters of Castle Hot Springs, Arizona.
American Journal of Science, NEW HAVEN, Ser. 5, Vol. 13, 1927, pp. 445–449.

BURKS, Marian R. See BATES, Robert Latimer, 4.

BUTLER, Arthur Pierce, Jr. See McKELVEY, Vincent Ellis, 62.

BUTLER, Bert Sylvenus
6. (and WILSON, Eldred Dewey; RASOR, Charles Alfred) Geology and Ore Deposits of the Tombstone District, Arizona.
Arizona State Bureau of Mines, TUCSON, Geological Series No. 10, Bulletin, No. 143, 1938, 114 pp.

BUTLER, Gurdon Montague
7. (and ALLEN, Milton Arthur) Uranium and Radium.
Arizona State Bureau of Mines, TUCSON, Mineral Technology Series No. 27, Bulletin, No. 117, 1921, 26 pp.

(See also ALLEN, Milton Arthur, 1)

CLIPPINGER, Donn Merrell
8. Barite of New Mexico.
New Mexico School of Mines, Bureau of Mines and Mineral Resources, SOCORRO, Circular, No. 21, 1949, 28 pp.

COOPER, Margaret
9. Preliminary Bibliography on Uranium and Thorium and Radioactive Carbonaceous Deposits.
U.S.A.E.C. RMO-835, November, 1951, 40 pp.
(Report issued by U.S.A.E.C. Technical Information Service, OAK RIDGE, Tenn.)

CROXTON, Fred E.
10. Uranium and Its Compounds—a Bibliography of Unclassified Literature.
Carbide and Carbon Chemicals Co., K-25 Plant, OAK RIDGE, Tenn. Report, K-295 Part 2, 1951, 708 pp.

DAKE, Henry Carl. See DeMENT, Jack Andrew 12, 13.

DAY, David Talbot
11. (and RICHARDS, Robert Hallowell) Useful Minerals in the Black Sands of the Pacific Slope.
U. S. Geological Survey, WASHINGTON, Mineral Resources of the United States for 1905, 1906, pp. 1175–1258.

DeMENT, Jack Andrew
12. (and DAKE, Henry Carl) Handbook of Uranium Minerals.
PORTLAND, Ore. (Mineralogist Publishing Company), 1948, 96 pp.

13. (and DAKE, Henry Carl) Uranium and Atomic Power.
NEW YORK (Chemical Publishing Co.) 2nd Ed., 1945, 343 pp.

DUNNING, Charles H.
14. Eighth Annual Report, July 1, 1946 to June 30, 1947.
Arizona Department of Mineral Resources, PHOENIX, Annual Report, No. 8, 1947, 27 pp. See pp. 11–13.

15. Ninth Annual Report, July 1, 1947 to June 30, 1948.
Arizona Department of Mineral Resources, PHOENIX, Annual Report, No. 9, 1948, 31 pp. See pp. 18–19.

16. Tenth Annual Report, July 1, 1948 to June 30, 1949.
Arizona Department of Mineral Resources, PHOENIX, Annual Report, No. 10, 1949, 24 pp. See pp. 17–19.

17. Eleventh Annual Report, July 1, 1949 to June 30, 1950.
Arizona Department of Mineral Resources, PHOENIX, Annual Report, No. 11, 1950, 36 pp. See pp. 18, 19, 20.

EBBLEY, Norman
18. Drilling for Uranium-Vanadium on the Colorado Plateau.
Mining and Contracting Review, SALT LAKE CITY, Vol. 51, No. 9, 1949, pp. 5–6, 14.

ELLIS, Robert Walpole
19. New Mexico Mineral Deposits Except Fuels.
University of New Mexico, ALBUQUERQUE, Bulletin, No. 167 (Geological Series, Vol. 4, No. 2), 1930, 148 pp. See pp. 39–40, 79–80 and 139.

EVERHART, Donald Lough
20. Geology of Uranium Deposits—A Condensed Version, with Mineral Tables by Muriel Mathez.
U.S.A.E.C. RMO-732, May, 1951, 33 pp.
(Open-file report issued by U.S.A.E.C. Technical Information Service, OAK RIDGE, Tenn.)

21. Reconnaissance Examinations of Copper-Uranium Deposits West of the Colorado River.

U.S.A.E.C. RMO-659, November, 1950, 19 pp. (Open-file report issued by U.S.A.E.C. Technical Information Service, OAK RIDGE, Tenn.)

FISCHER, Richard Philip
22. Uranium-Bearing Sandstone Deposits of the Colorado Plateau.
Economic Geology, LANCASTER, Vol. 45, 1950, pp. 1–11.

(See also McKELVEY, Vincent Ellis, 62.)

GALBRAITH, Frederic William
23. Minerals of Arizona.
Arizona State Bureau of Mines, TUCSON, Geological Series No. 15, Bulletin, No. 149, 1941, 82 pp. See pp. 53, 55, 62–63, 67.

24. Minerals of Arizona, 2nd Ed. (Revised)
Arizona State Bureau of Mines, TUCSON, Geological Series No. 17, Bulletin, No. 153, 1947, 101 pp. See pp. 39–40, 55, 60, 87, 89, 90.

GARDINER, Lynn. See GRUNER, John Walter, 29.

GEORGE, D'Arcy
25. Mineralogy of Uranium and Thorium Bearing Minerals. Revised January 1949.
U.S.A.E.C. RMO-563, 1950, 198 pp. (Report issued by U.S.A.E.C. Technical Information Service, OAK RIDGE, Tenn.)

GIANELLA, Vincent Paul
26. Bibliography of the Geologic Literature of Nevada.
University of Nevada, RENO, Bulletin, Vol. 39, No. 6 (Geology and Mining Series, No. 43), 1945, pp. 9–188.

Includes some references on uranium occurrences.

(See also SMITH, Ward Conwell, 84.)

GORDON, Charles Henry. See LINDGREN, Waldemar, 60.

GOTT, Garland B.
27. (and WYANT, Donald Gray; BERONI, Ernest P.) Uranium in Black Shales, Lignites, and Limestones in the United States.
Geological Society of America, NEW YORK, Bulletin, Vol. 62, 1951, p. 1535. (Abstract of paper given at G.S.A. Rocky Mt. Section meeting, April 13–14, 1951.)

GRANGER, H. C.
28. (and BAUER, Herman L., Jr.) Results of Diamond Drilling, Merry Widow Claim, White Signal, Grant County, New Mexico.
U. S. Geological Survey TEM-146A, (issued) November 13, 1951, 11 pp. (Open-file report prepared by U.S.G.S. for U.S.A.E.C. and issued by U.S.A.E.C. Technical Information Service, OAK RIDGE, Tenn.)

GRATON, Louis Caryl. See LINDGREN, Waldemar, 60.

GRIMALDI, Frank Saverio. See AXELROD, Joseph Meyer, 3.

GRUNER, John Walter
29. (and TOWLE, Charles Carroll, Jr.; GARDINER, Lynn) Uranium Mineralization in Todilto Limestone near Grants, McKinley County, New Mexico.
Geological Society of America, NEW YORK, Bulletin, Vol. 62, 1951, p. 1445; and Economic Geology, LANCASTER, Vol. 46, 1951, p. 802. (Abstract of paper given at G.S.A.-S.E.G. meetings, Nov. 1951.)

GUILD, F. N.
30. The Mineralogy of Arizona.
EASTON, Pa. (Chemical Publishing Co.), 1910, 103 pp.

HAHN, A. D. See ROTHROCK, Howard Eugene, 76.

HEINEMAN, Robert Emil S.
31. A Note on the Occurrence of Monazite in Western Arizona.
American Mineralogist, MENASHA, Vol. 15, 1930, pp. 536–537.

HERSHEY, Robert L.
32. Tables of Fluorescent and Radioactive Minerals.
New Mexico School of Mines, Bureau of Mines and Mineral Resources, SOCORRO, Circular, No. 15, 1947, 14 pp.

HESS, Frank L.
33. Radium, Uranium, and Vanadium.
Engineering and Mining Journal, NEW YORK, Vol. 127, No. 3, 1929, p. 101.

34. Uranium, Vanadium, Radium, Gold, Silver, and Molybdenum Sedimentary Deposits.
"Ore Deposits of the Western States," NEW YORK (A.I.M.E. Lindgren Memorial Volume) 1933, pp. 450–480.

35. (and WELLS, Roger Clark) Samarskite from Petaca, New Mexico.
American Journal of Science, NEW HAVEN, Ser. 5, Vol. 19, 1930, pp. 17–26.

HEWETT, Donnel Foster
36. Carnotite Discovered near Aguila, Arizona.
Engineering and Mining Journal, NEW YORK, Vol. 120, No. 1, 1925, p. 19.

37. Carnotite in Southern Nevada.
Engineering and Mining Journal, NEW YORK, Vol. 115, 1923, pp. 232–235.

38. Central Arizona Holds Deposits of Carnotite.
Mining Journal, PHOENIX, Vol. 9, No. 7, 1925, pp. 49–50.

HILL, James Madison
39. Notes on Some Mining Districts in Eastern Nevada
U. S. Geological Survey, WASHINGTON, Bulletin, No. 648, 1916, 214 pp. See pp. 39 and 119.

(See also SCHRADER, Frank Charles, 81)

JAFFE, Howard William. See KAUFFMAN, Albert John, Jr., 44.

JOHNSON, Charles Harvey. See ROTHROCK, Howard Eugene, 76

JONES, Fayette Alexander
40. The Mineral Resources of New Mexico.
New Mexico School of Mines, State Bureau of Mines and Mineral Resources, SOCORRO, Bulletin, No. 1, 1915, 77 pp.

JOSEPH, Phineas Eleasor
41. Vanadium.
Arizona State Bureau of Mines, TUCSON, Mineral Technology Series No. 9, Bulletin, No. 18, 1915, 10 pp.

JUST, Evan
42. Geology and Economic Features of the Pegmatites of Taos and Rio Arriba Counties, New Mexico.
New Mexico School of Mines, Bureau of Mines and Mineral Resources, SOCORRO, Bulletin, No. 13, 1937, 73 pp.

KAISER, Edward P.
43. Uraniferous Quartzite, Red Bluff Prospect, Gila County, Arizona.
U. S. Geological Survey, WASHINGTON, Circular, No. 137, 1951, 10 pp.

KAUFFMAN, Albert John, Jr.
44. (and JAFFE, Howard William) Chevkinite (Tscheffkinite) from Arizona.
American Mineralogist, MENASHA, Vol. 31, 1946, pp. 582–588.

KEEVIL, Norman Bell
45. Radioactivity and Mineral Deposits.
American Mineralogist, MENASHA, Vol. 35, 1950, pp. 816–833.

KENNAN, Chester T.
46. Some Ore Deposits in Sandstone.
Mining Science, DENVER, Vol. 71, March 1915, pp. 21–23.

KENNEDY, G. R.
47. Shiprock Uranium Sampler.
Engineering and Mining Journal, NEW YORK, Vol. 153, No. 4, 1952, pp. 86–88.

KERR, Paul Francis
48. The Earth's Uranium.
Scientific American, NEW YORK, Vol. 184, No. 5, 1951, pp. 17–21.

KEYES, Charles Rollin
49. New Mexico in 1905.
Engineering and Mining Journal, NEW YORK, Vol. 81, 1906, pp. 22–23.

50. Rare Metals from New Mexico.
Pan-American Geologist, DES MOINES, Vol. 39, 1923, pp. 79–80.

KING, John W.
51. Geology and Ore Deposits of Mesa V, Lukachukai District, Arizona.
U.S.A.E.C. RMO-754, (issued) November 16, 1951, 17 pp. (Open-file report issued by U.S.A.E.C. Technical Information Service, OAK RIDGE, Tenn.)

52. Reconnaissance of Red Rock District, Cove Mesa, and Kinusta (Tree) Mesa, Arizona.
U.S.A.E.C. RMO-755, February 1, 1951, 11 pp. (Open-file report issued by U.S.A.E.C. Technical Information Service, OAK RIDGE, Tenn.)

KNOERR, Alvin William
53. Uranium.
Engineering and Mining Journal, NEW YORK, Vol. 153, No. 2, 1952, pp. 92–94.

LASKY, Samuel Grossman
54. (and WOOTTON, Thomas Peltier) The Metal Resources of New Mexico and Their Economic Features.
New Mexico School of Mines, State Bureau of Mines and Mineral Resources, SOCORRO, Bulletin, No. 7, 1933, 178 pp. See pp. 35, 67, 89–90, 139.

LEACH, Albert A.
55. The Geology and History of the Malone Mines.
Mining Journal, PHOENIX, Vol. 12, No. 15, 1928, pp. 5–6, 34.

56. The Mining of Radium Ore in New Mexico.
Mining Journal, PHOENIX, Vol. 10, No. 22, 1927, pp. 3–4.

LEACH, F. I.
57. Radium Ore Discovered in White Signal District, N. M.
Engineering and Mining Journal, NEW YORK, Vol. 109, 1920, p. 989.

LEE, O. Ivan
58. Notes and News of Minerals of the Rare Elements.
Rocks and Minerals, PEEKSKILL, Vol. 2, 1927, pp. 100–101.

LINCOLN, Francis Church
59. Mining Districts and Mineral Resources of Nevada.
RENO (Nevada Newsletter Publishing Co.), 1923, 295 pp. See pp. 27–29, 118, 283, and 288.

LINDGREN, Waldemar
60. (and GRATON, Louis Caryl; GORDON, Charles Henry)
The Ore Deposits of New Mexico.
U. S. Geological Survey, WASHINGTON, Professional Paper, No. 68, 1910, 361 pp. See pp. 80–81 and 162.

LUTRELL, Estelle
61. Bibliography of Literature on Arizona Mining, Metallurgy, and Geology.
Arizona State Bureau of Mines, TUCSON, Economic Series No. 7, Bulletin, No. 23, 1915, 49 pp.

Includes references on uranium and carnotite deposits in Arizona.

McKELVEY, Vincent Ellis
62. (and PAGE, Lincoln Ridler; FISCHER, Richard Philip; BUTLER, Arthur Pierce, Jr.) Uranium Deposits in the United States.
Economic Geology, LANCASTER, Vol. 47, 1952, pp. 125–126.
(Abstract of paper given at A.I.M.E.–S.E.G. meetings, New York, February 18–20, 1952.)

MATHEZ, Muriel. See EVERHART, Donald Lough, 20.

MERRITT, Phillip Leonidas
63. Uranium and the Petroleum Industry.
U.S.A.E.C., WASHINGTON, 5 pp. (mimeo.) (Speech given before the American Association of Petroleum Geologists, April 26, 1951.)

MILTON, Charles. See AXELROD, Joseph Meyer, 3.

MONTGOMERY, Arthur
64. Geochemistry of Tantalum in the Harding Pegmatite, Taos County, New Mexico. American Mineralogist, MENASHA, Vol. 35, 1950, pp. 853–866.

65. The Harding Pegmatite—Remarkable Storehouse of Massive White Beryl. Mining World, SAN FRANCISCO, Vol. 13, No. 8, 1951, pp. 32–35; World Mining, SAN FRANCISCO, Vol. 4, No. 8, 1951, pp. 32–35.

MUENCH, Oscar Brauer
66. Glorieta Monazite. American Chemical Society, NEW YORK, Journal, Vol. 60, 1938, pp. 2661–2662.

67. Glorieta Monazite. Pan-American Geologist, DES MOINES, Vol. 70, No. 1, 1938, p. 73. (Abstract)

68. Recent Analyses for Age by Lead Ratios. Geological Society of America, NEW YORK, Bulletin, Vol. 61, 1950, pp. 129–132.

MURATA, Kiguma Jack. See AXELROD, Joseph Meyer, 3.

NORTHROP, Stuart Alvord
69. Minerals of New Mexico. University of New Mexico, ALBUQUERQUE, Bulletin, No. 379 (Geol. Ser., Vol. 6, No. 1), 1942, 387 pp.

PAGE, Lincoln Ridler
70. Uranium in Pegmatites. Economic Geology, LANCASTER, Vol. 45, 1950, pp. 12–34.

(See also McKELVEY, Vincent Ellis, 62.)

PELLEGRIN, A. L.
71. Rare Minerals in Southern Arizona. Mining World, CHICAGO, Vol. 34, 1911, p. 450.

RAPAPORT, Irving. See TOWLE, Charles Carroll, Jr., 88 and 89.

RASOR, Charles Alfred. See BUTLER, Bert Sylvenus, 6.

REAGAN, Albert B.
72. Mineral Resources of the Navajo Country. Mining Journal, PHOENIX, Vol. 11, No. 18, 1928, pp. 3–4, 15.

RICHARDS, Robert Hallowell. See DAY, David Talbot, 11.

RICHARDSON, James K.
73. Unprecedented Expansion in the Mining Industry. Mining Engineering, NEW YORK, Vol. 4, 1952, pp. 351–355. See p. 355.

RITTENHOUSE, Gordon
74. Sources of Modern Sands in the Middle Rio Grande Valley, New Mexico. Journal of Geology, CHICAGO, Vol. 52, 1944, pp. 145–183.

75. Transportation and Deposition of Heavy Minerals. Geological Society of America, NEW YORK, Bulletin, Vol. 54, 1943, pp. 1725–1780.

ROTHROCK, Howard Eugene
76. (and JOHNSON, Charles Harvey; HAHN, A. D.) Fluorspar Resources of New Mexico. New Mexico School of Mines, Bureau of Mines and Mineral Resources, SOCORRO, Bulletin, No. 21, 1946, 239 pp. See pp. 26, 33, 110, 112, 113, and 116.

ROVE, Olaf N.
77. Mining Geology. Mining Engineering, NEW YORK, Vol. 4, 1952, pp. 140–143.

SANFORD, Samuel
78. (and STONE, Ralph Walter) Useful Minerals of the United States. U. S. Geological Survey, WASHINGTON, Bulletin, No. 585, 1914, 250 pp.

(See also SCHRADER, Frank Charles, 82.)

SCHRADER, Frank Charles
79. A Reconnaissance of the Jarbridge, Contact, and Elk Mountain Mining Districts, Elko County, Nevada. U. S. Geological Survey, WASHINGTON, Bulletin, No. 497, 1912, 162 pp. See p. 113.

80. Notes on Ore Deposits at Cave Valley, Patterson District, Lincoln County, Nevada. University of Nevada, RENO, Bulletin, Vol. 25, No. 3, 1931, 16 pp.

81. (and HILL, James Madison) Mineral Deposits of the Santa Rita and Patagonia Mountains, Arizona. U. S. Geological Survey, WASHINGTON, Bulletin, No. 582, 1915, 373 pp.

82. (and STONE, Ralph Walter; SANFORD, Samuel) Useful Minerals of the United States. U. S. Geological Survey, WASHINGTON, Bulletin, No. 624, 1917, 412 pp.

SMITH, Ida
83. Mineralogical Society of Arizona. Rocks and Minerals, PEEKSKILL, Vol. 24, 1949, p. 626.

SMITH, Ward Conwell
84. (and GIANELLA, Vincent Paul) Tin Deposit at Majuba Hill, Pershing County, Nevada. U. S. Geological Survey, WASHINGTON, Bulletin, No. 931-C, 1942, pp. 39–55.

STAATZ, Mortimer Hay
85. (and BAUER, Herman L., Jr) Virgin Valley Opal District, Humboldt County, Nevada. U. S. Geological Survey, WASHINGTON, Circular, No. 142, 1951 [1952], 7 pp.

(See also WILMARTH, V. R., 95.)

STAVER, W. H.
86. Radium Ore Supply Not Limited. Engineering and Mining Journal, NEW YORK, Vol. 112, 1921, p. 405.

STOKES, William Lee
87. Carnotite Deposits in the Carrizo Mountains Area, Navajo Indian Reservation, Apache County, Arizona, and San Juan County, New Mexico. U. S. Geological Survey, WASHINGTON, Circular, No. 111, May 1951, 5 pp.

STONE, Ralph Walter. See SANFORD, Samuel, 78; SCHRADER, Frank Charles, 82.

TOWLE, Charles Carroll, Jr.
88. (and RAPAPORT, Irving) Development of Uranium Mining in the Grants, New Mexico, Area.
Economic Geology, LANCASTER, Vol. 47, 1952, p. 128. (Title only of paper given at A.I.M.E.S.E.G. meetings, New York, Feb. 18–20, 1952.)

89. (and RAPAPORT, Irving) Uranium Deposits of the Grants District, New Mexico.
Economic Geology, LANCASTER, Vol. 47, 1952, p. 128. (Abstract of paper given at A.I.M.E.-S.E.G. meetings, New York, Feb. 18–20, 1952.)

(See also GRUNER, John Walter, 29.)

U.S.A.E.C. & U.S.G.S.

90. Prospecting for Uranium.
WASHINGTON (Government Printing Office), 1949, 123 pp.; (revised) October, 1951, 128 pp.

U.S.G.S. See U.S.A.E.C., 90.

WARING, W. George
91. Boro-silicate of Uranium.
Engineering and Mining Journal, NEW YORK, Vol. 49, 1890, p. 356.

WELLS, Edgar Herbert
92. An Outline of the Mineral Resources of New Mexico.
New Mexico School of Mines, State Bureau of Mines and Mineral Resources, SOCORRO, Circular, No. 1 (Revised), 1930. 15 pp. See p. 6.

93. The Mining Industry and Mineral Resources of New Mexico.
Mining Congress Journal, WASHINGTON, Vol. 10, 1924, pp. 397–398.

WELLS, Roger Clark. See HESS, Frank L., 35.

WILLIS, Charles Francis
94. Prince of Arizona.
Mining Journal, PHOENIX, Vol. 3, No. 11, 1920, pp. 38–39.

WILMARTH, V. R.
95. (and BAUER, Herman L.; STAATZ, M. H.; WYANT, Donald Gray) Uranium in Fluorite Deposits.
Geological Society of America, NEW YORK, Bulletin, Vol. 62, 1951, pp. 1543–1544. (Abstract of paper given at G.S.A. Rocky Mountain Section meetings, April 13–14, 1951.)

WILSON, Eldred Dewey
96. Bibliography of the Geology and Mineral Resources of Arizona.
Arizona State Bureau of Mines, TUCSON, Geological Series No. 13, Bulletin, No. 146, 1939, 164 pp.

Includes references to uranium and thorium occurrences

97. Geology and Mineral Deposits of Southern Yuma County, Arizona.
Arizona State Bureau of Mines, TUCSON, Geological Series No. 7, Bulletin, No. 134, 1933, 234 pp. See p. 220.

(See also BUTLER, Bert Sylvenus, 6.)

WOOD, John A.
98. Spiral Concentrator Recovers Tantalum Ores at the Harding Mine.
Mining Congress Journal, WASHINGTON, Vol. 32, No. 1, 1946, pp. 44–45.

WOOTTON, Thomas Peltier
99. Mineral Resources of New Mexico.
Mining Journal, PHOENIX, Vol. 8, No. 18, 1925, pp. 9–10, 21. See p. 21.

(See also LASKY, Samuel Grossman, 54.)

WRIGHT, Lauren Albert
100. The Globe Pegmatite, Rio Arriba County, New Mexico.
American Journal of Science, NEW HAVEN, Vol. 246, 1948, pp. 665–688.

WRIGHT, Robert James
101. Annie Laurie Prospect, Santa Cruz County, Arizona.
U.S.A.E.C. RMO-677, January 1951, 8 pp. (Open-file report issued by U.S.A.E.C. Technical Information Service, OAK RIDGE, Tenn.)

102. Current Status of Atomic Raw Materials.
Earth Science Digest, REVERE, Mass., Vol. 4, No. 12, July, 1950, pp. 3–8; Vol. 5, No. 1, Aug. 1950, pp. 3–10.

103. Reconnaissance of Certain Uranium Deposits in Arizona.
U.S.A.E.C. RMO-679, December 1950, 21 pp. (Open-file report issued by U.S.A.E.C. Technical Information Service, OAK RIDGE, Tenn.)

WYANT, Donald Gray. See GOTT, Garland B., 27; WILMARTH, V. R., 95.

Anonymous Notes, 1902–1952

104. Production of Rare Minerals.
Mining and Scientific Press, SAN FRANCISCO, Vol. 84, 1902, p. 281.

105. General Mining News: Arizona-Yavapai County.
Mining and Scientific Press, SAN FRANCISCO, Vol. 104, 1912, p. 255.

106. Nevada-Churchill County.
Engineering and Mining Journal, NEW YORK, Vol. 96, 1913, p. 1239.

107. New Mexico.
Mining and Engineering World, CHICAGO, Vol. 41, 1914, p. 168.

108. Directory of Arizona Minerals. Second Issue.
Arizona State Bureau of Mines, TUCSON, Mineral Technology Series No. 1, Bulletin, No. 3, 1915, pp. 3–16. See pp. 4 and 8.

109. Mineralogy of Useful Minerals in Arizona.
Arizona State Bureau of Mines, TUCSON, Economic Series No. 11, Bulletin, No. 41, 1916, 70 pp. See pp. 25, 35–36.

110. Pima County—Ajo District—Has Mine of Pitchblende.
Mining Journal, PHOENIX, Vol. 1, No. 3, 1917, p. 21.

111. A New, and Hitherto Unknown, Uranium Mineral.
Mining Journal, PHOENIX, Vol. 4, No. 5, 1920, p. 59.

112. News by Mining Districts. New Mexico. White Signal.
Engineering and Mining Journal, NEW YORK, Vol. 110, 1920, p. 789.

113. Radium in New Mexico.
Mining Journal, PHOENIX, Vol. 3, No. 12, 1920, p. 24.

114. That Radium-bearing Ores Are Found.
Mining Journal, PHOENIX, Vol. 4, No. 5, 1920, p. 59.

115. Radium-bearing Torbernite.
Mining Congress Journal, WASHINGTON, Vol. 7, 1921, p. 265.

116. Concentrated Mining Activities from Arizona, New Mexico, and Old Mexico.—Coconino.
Mining Journal, PHOENIX, Vol. 6, No. 6, 1922, p. 13.

117. Monazite Found in Nevada.
Queensland Government Mining Journal, BRISBANE, Vol. 23, 1922, p. 247.

118. Vanadium (and Uranium).
Mining Congress Journal, WASHINGTON, Vol. 8, 1922, p. 985–986.

119. It is Reported from Octave, Arizona.
Mining Journal, PHOENIX, Vol. 7, No. 14, 1923, p. 31.

120. Milton Ray of Aguila, Arizona.
Mining Journal, PHOENIX, Vol. 9, No. 4, 1925, p. 30.

121. The Ra-Tor Mining and Manufacturing Company.
Mining Journal, PHOENIX, Vol. 12, No. 5, 1928, p. 26.

122. Clay Bearing Rare Mineral Located in Equarius Section.
Mining Journal, PHOENIX, Vol. 13, No. 12, 1929, p. 56.

123. J. F. Barnhill, Mining Man and Chemist, Is Said to Have Discovered Uranium.
Mining Journal, PHOENIX, Vol. 13, No. 21, 1930, p. 39.

124. Shipment of Two Cars of Material by the Smithsonian Institution.
Mining Journal, PHOENIX, Vol. 14, No. 15, 1930, p. 29.

125. Gila County Mine Develops Many Semi-Rare Minerals.
Mining Journal, PHOENIX, Vol. 14, No. 24, 1931, p. 18.

126. Metal and Nonmetal Occurrences in Nevada.
University of Nevada, RENO, Bulletin, Vol. 26, No. 6, 1932, 129 pp. See pp. 26, 51.

127. The Merry Widow Mine.
Mining Journal, PHOENIX, Vol. 16, No. 9, 1932, p. 25.

128. Nevada—The Cambridge Mining Company.
Mining Journal, PHOENIX, Vol. 25, No. 18, 1942, p. 29.

129. Nevada . . . Canadian Radium-Uranium Company Is Interested in Prospecting.
Mining Journal, PHOENIX, Vol. 29, No. 2, 1945, p. 30.

130. Uranium Deposits.
Engineering and Mining Journal, NEW YORK, Vol. 146, No. 10, 1945, p. 132.

131. Reports Have Indicated Early Action by the U. S. Bureau of Mines in Exploring Deposits Containing Uranium at Round Mountain in Nye County.
Engineering and Mining Journal, NEW YORK, Vol. 147, No. 10, 1946, p. 100.

132. Tests Are Reported to Show the Presence of Uranium in Ore from the Heneberg Property in the Round Mountain District of Nye County, Nevada.
Mining Journal, PHOENIX, Vol. 29, No. 17, 1946, p. 26.

133. Uranium Ore Find Located in Nevada.
California Mining Journal, AUBURN, Vol. 15, May 1946, p. 28.

134. Uranium Ore Located.
Mining Congress Journal, WASHINGTON, Vol. 32, No. 6, 1946, p. 69.

135. Uranium Discoveries.
California Mining Journal, AUBURN, Vol. 16, May 1947, p. 1.

136. According to . . . Charles H. Dunning, Director of the Arizona Department of Mineral Resources, Huge Deposits of Uranium-Bearing Ores Lie Undeveloped in Northwestern Arizona.
Engineering and Mining Journal, NEW YORK, Vol. 149, No. 1, 1948, p. 110.

137. Nevada Uranium Starts Work at Round Mountain Mine.
Mining and Industrial News, SAN FRANCISCO, Vol. 16, No. 11, 1948, p. 15.

138. New Uranium Minerals.
Mineralogist, PORTLAND, Vol. 16, 1948, p. 596.

139. Reno Firm to Test, Assay Radium Ores.
Mining and Industrial News, SAN FRANCISCO, Vol. 16, No. 11, 1948, p. 15.

140. Terms for Uranium Ores from Indian Reservations.
Mining Congress Journal, WASHINGTON, Vol. 34, No. 12, 1948, p. 73.

141. Arthur Montgomery, Lessee of the Harding Mine in Taos County, Is Preparing for a Small Beryl Operation.
Engineering and Mining Journal, NEW YORK, Vol. 150, No. 11, 1949, pp. 138–139.

142. Petrified Wood Yields Commercial Uranium.
Engineering and Mining Journal, NEW YORK, Vol. 150, No. 6, 1949, p. 89.

143. Reno Firm Takes Nevada Holdings of Central Comstock.
Mining and Industrial News, SAN FRANCISCO, Vol. 17, No. 2, 1949, p. 16.

144. Southwest Uranium Mining Activities with Special Emphasis on Arizona Developments.
Mining World, SAN FRANCISCO, Vol. 11, No. 8, 1949, p. 17.

145. The State Tax Commission Has Ruled that Uranium and Gold Mined in Arizona Is Subject to the State Sales Tax.
Engineering and Mining Journal, NEW YORK, Vol. 150, No. 11, 1949, p. 127.

146. Unique Uranium Ore.
Mining Congress Journal, WASHINGTON, Vol. 35, No. 6, 1949, p. 103.

147. Uranium and Vanadium in Navajo Reserve.
Mining Journal, LONDON, Vol. 233, No. 5952, 1949, p. 872.

148. Western United States.
Mining Journal, LONDON, Vol. 233, No. 5945, 1949, p. 679.

149. Arizona. Atomic Ore Production.
Engineering and Mining Journal, NEW YORK, Vol. 151, No. 3, 1950, p. 113.

150. Arizona. F. A. Sitton . . . Has Started Uranium Operations on the Navajo Reservation.
Engineering and Mining Journal, NEW YORK, Vol. 151, No. 11, 1950, p. 121.

151. Arizona . . . Hillside Mine.
Engineering and Mining Journal, NEW YORK, Vol. 151, No. 6, 1950, p. 113.

152. Arizona. Ore Samples from the Papago Chief Mine.
Engineering and Mining Journal, NEW YORK, Vol. 151, No. 6, 1950, p. 113.

153. Colorado . . . Uranium Ore.
Engineering and Mining Journal, NEW YORK, Vol. 151, No. 12, 1950, p. 131.

154. Diamond Drilling for Uranium on the Colorado Plateau.
Engineering and Mining Journal, NEW YORK, Vol. 151, No. 10, 1950, pp. 86–88.

155. Nevada. A Deposit of Low-Grade Uranium.
Engineering and Mining Journal, NEW YORK, Vol. 151, No. 12, 1950, p. 140.

156. Nevada. Reports of Finding a Deposit of Low-Grade Uranium Ore near Midas.
Engineering and Mining Journal, NEW YORK, Vol. 151, No. 7, 1950, p. 106.

157. Nevada Uranium.
Mineralogist, PORTLAND, Vol. 18, 1950, p. 122.

158. Nevada . . . . Uranium Production Co.
Engineering and Mining Journal, NEW YORK, Vol. 151, No. 4, 1950, p. 142.

159. New Mexico, E. B. Killion, Silver City.
Engineering and Mining Journal, NEW YORK, Vol. 151, No. 3, 1950, p. 123.

160. New Mexico. Mining Activity at Organ.
Engineering and Mining Journal, NEW YORK, Vol. 151, No. 1, 1950, p. 116.

161. One of the Big Pieces of Mining News in the Southwest.
Engineering and Mining Journal, NEW YORK, Vol. 151, No. 11, 1950, p. 135.

162. Rare Earths Found.
Mineralogist, PORTLAND, Vol. 18, 1950, p. 459.

163. A New Bonus Offer Is Being Made by the U. S. Atomic Energy Commission.
Engineering and Mining Journal, NEW YORK, Vol. 152, No. 10, 1951, p. 121.

164. A 200-Ton Mill to Process Uranium Found in Limestone May Be Constructed.
Mining Engineering, NEW YORK, Vol. 3, 1951, p. 311.

165. A Uranium Deposit That May Prove to Be One of the Nation's Largest Has Been Found between Grants and Gallup, N. M.
Mining Engineering, NEW YORK, Vol. 3, 1951, p. 30.

166. Arizona. In Northern Arizona.
Engineering and Mining Journal, NEW YORK, Vol. 152, No. 7, 1951, p. 160.

167. Arizona. Uranium Ore.
Engineering and Mining Journal, NEW YORK, Vol. 152, No. 6, 1951, p. 112.

168. Central Arizona's First Uranium Ore Shipment.
Engineering and Mining Journal, NEW YORK, Vol. 152, No. 11, 1951, pp. 106, 130.

169. Development of the Last Frontier.
Mining World, SAN FRANCISCO, Vol. 13, No. 4, 1951, pp. 3, 6.

170. Jack Knabel, Representing Anaconda Copper Mining Co., Which is Exploring Uranium Deposits West of Grants.
Engineering and Mining Journal, NEW YORK, Vol. 152, No. 11, 1951, p. 140.

171. Nevada. Discovery of Radioactive Ore.
Engineering and Mining Journal, NEW YORK, Vol. 152, No. 2, 1951, p. 159.

172. New Mexico. Another Development.
Engineering and Mining Journal, NEW YORK, Vol. 152, No. 7, 1951, p. 190.

173. New Mexico. Santa Fe Railroad Mining Engineers Testing Todilto Limestone Deposits.
Engineering and Mining Journal, NEW YORK, Vol. 152, No. 8, 1951, p. 120.

174. New Mexico. The Santa Fe Railway Co.
Engineering and Mining Journal, NEW YORK, Vol. 152, No. 6, 1951, p. 133.

175. New Mexico. The Town of Grants.
Engineering and Mining Journal, NEW YORK, Vol. 152, No. 2, 1951, p. 160.

176. Santa Fe Railway Company Evaluates Grants, New Mexico, Uranium Deposits. Mining World, SAN FRANCISCO, Vol. 13, No. 4, 1951, pp. 37, 58.

177. To Exploit Uranium on its Lands, Santa Fe Railway Co. Formed a. . .Subsidiary. Engineering and Mining Journal, NEW YORK, Vol. 152, No. 12, 1951, p. 139.

178. Utah. . .Members of the Navajo Tribe May Reassign Mining Permits. Engineering and Mining Journal, NEW YORK, Vol. 152, No. 2, 1951, p. 163.

179. William Heim, Corona, Is Operating a New Mill Designed to Process Bastnasite. Engineering and Mining Journal, NEW YORK, Vol. 152, No. 11, 1951, p. 140.

180. AEC Has Signed a Contract to Buy Uranium Concentrates from a Processing Plant to be Built by Anaconda Copper Mining Co. in the Vicinity of Grants. Engineering and Mining Journal, NEW YORK, Vol. 153, No. 3, 1952, p. 137.

181. Anaconda Copper Mining Co. Engineering and Mining Journal, NEW YORK, Vol. 153, No. 1, 1952, p. 134.

182. Anaconda to Supply Uranium. Mining Engineering, NEW YORK, Vol. 4, 1952, p. 343.

183. Companies Join with Heim to Develop Bastnasite. Engineering and Mining Journal, NEW YORK, Vol. 153, No. 1, 1952, p. 108.

184. In 1951, Arizona's Uranium Production Rose. Engineering and Mining Journal, NEW YORK, Vol. 153, No. 2, 1952, pp. 163, 165.

185. Navajo Uranium Co. Engineering and Mining Journal, NEW YORK, Vol. 153, No. 2, 1952, p. 176.

186. Navajo Uranium Co., Cortez, Colo. Engineering and Mining Journal, NEW YORK, Vol. 153, No. 3, 1952, p. 137.

187. No Change in AEC Bonus. Engineering and Mining Journal, NEW YORK, Vol. 153, No. 3, 1952, p. 105.

188. Using a Bulldozer, Gus Rogers and Ed Bottomley Have Opened Up Another 110 ft. of their Pitchblende Vein. Engineering and Mining Journal, NEW YORK, Vol. 153, No. 1, 1952, p. 132.

INDEX I

GAZETTEER FOR ARIZONA, NEVADA, AND NEW MEXICO

(Numbers refer to References Listed in Bibliography)

A

A. A. Leach claims: See New Mexico-Grant Co., 113.
Acme claim: See New Mexico-Grant Co., 57.
Aguila: See Arizona-Maricopa Co., 2, 23, 24, 36, 38, 120.
Ajo Mining District: See Arizona-Pima Co., 110.
All American prospect: See New Mexico-Lincoln Co., 76.
Annie Laurie claims: See Arizona-Santa Cruz Co., 103.
Annie Laurie prospect: See Arizona-Santa Cruz Co., 101.
Antelope (or Cedar) Mining District: See Nevada-Pershing Co., 84.
Aquarius Mts. (or Range): See Arizona-Mohave Co., 2, 23, 24, 44, 122.
Arroyo: See New Mexico-Santa Fe Co., 69.
Atlanta mine: See Nevada-Lincoln Co., 26, 37, 39, 82, 126.
Atlanta Mining District: See Nevada-Lincoln Co., 26, 37, 59.

B

Bagdad: See Arizona-Yavapai Co., 2, 3, 17, 23, 24, 83, 103, 138, 151.
Banner mine: See Arizona-Pima Co., 103.
Bayard station: See New Mexico-Grant Co., 114.
Beardsley station: See Arizona-Maricopa Co., 94.
Beryl Prospect: See New Mexico-Rio Arriba Co., 42.
Big Burro Mt.: See New Mexico-Grant Co., 56.
Big Ledge claims: See Arizona-Mohave Co., 103.
Big Sandy River: See Arizona-Mohave Co., 2, 23, 24.
Bisbee: See Arizona-Cochise Co., 2, 23, 24, 34.
Black Canyon Creek: See Arizona-Yavapai Co., 11.
Black Dike claims: See Arizona-Pima Co., 103.
Black Hawk camp: See New Mexico-Grant Co., 57.
Black Hawk Mining District: See New Mexico-Grant Co., 69.
Black Hills near Jerome: See Arizona-Yavapai Co., 2, 23, 24.
Bluewater: See New Mexico-Valencia Co., 177, 181.
Bosque: See New Mexico-Valencia Co., 75.
Bradshaw Mts.: See Arizona-Yavapai Co., 5.
Brushy Basin member, Morrison fm.: See New Mexico-McKinley Co., 77.
Brushy Basin sandstone: See New Mexico-Valencia Co., 53.
Bull Creek: See New Mexico-San Miguel Co., 68, 69.
Bullard's Peak: See New Mexico-Grant Co., 57.
Burro Creek: See Arizona-Mohave Co., 2, 23, 24.
Burro Mts.: See New Mexico-Grant Co., 55, 56.

C

Caliente: See Nevada-Lincoln Co., 123.
Cambridge Mining Co.: See Nevada-Lyon Co., 128.
Camp Kithil: See New Mexico-Grant Co., 111, 112.
Canada la Jarita: See New Mexico-Rio Arriba Co., 42.
Carrizo: See Arizona-Apache Co., 144.
Carrizo Mts.: See Arizona-Apache Co., 2, 7, 23, 24, 52, 86, 87, 154.
Carrizo Mts.: See New Mexico-San Juan Co., 54, 69, 86, 87.
Carson City: See Nevada-Ormsby Co., 11, 59, 78, 82.
Castle Dome mine: See Arizona-Gila Co., 2, 24.
Castle Hot Springs: See Arizona-Yavapai Co., 5.

Cave Valley cave: See Nevada-Lincoln Co., 80.
Cave Valley mine: See Nevada-Lincoln Co., 80, 123.
Cedar Mining District: See Nevada-Pershing Co.-Antelope Mining District, 84.
Central Mining District: See New Mexico-Grant Co., 114.
Cerbat Range: See Arizona-Mohave Co., 2, 23, 24.
Cerrillos Hills: See New Mexico-Santa Fe Co., 69.
Cerrillos Mining District: See New Mexico-Santa Fe Co., 69.
Chama River: See New Mexico-Rio Arriba Co., 40, 69.
Chemehuevis Mining District: See Arizona-Mohave Co., 2, 23, 24, 31.
Chinle fm.: See Arizona-Navajo Co., 144.
Clark Mt.: See Nevada-Clark Co., 162.
Cochiti Mining District: See New Mexico-Sandoval Co., 40, 54, 60, 69.
Colorado Springs: See Colorado-El Paso Co., 188.
Columbia: See Arizona-Yavapai Co., 105.
Contact Mining District: See Nevada-Elko Co., 79.
Copper Hill: See New Mexico-Valencia Co., 107.
Cottonwood Mts.: See Arizona-Mohave Co., 103.
Cove Mesa: See Arizona-Apache Co., 52, 144.
Cribbenville mine: See New Mexico-Rio Arriba Co., 19, 42, 66, 69.
Cribbenville Mining District: See New Mexico-Rio Arriba Co.-Petaca Mining District, 19.
Cribbensville: See Cribbenville, New Mexico-Rio Arriba Co., 42.

D

Dripping Springs quartzite: See Arizona-Gila Co., 43.
Dry Springs: See Arizona-Santa Cruz Co., 103.

E

Eagle Nest claim No. 2: See New Mexico-Lincoln Co., 8.
Eagle Nest prospect: See New Mexico-Lincoln Co., 76.
Elizabethtown: See New Mexico-Colfax Co., 104.
Elk Mt.: See New Mexico-San Miguel Co., 69.
Entrada fm.: See Colorado Plateau, 63.
Equarius Mts.: See Aquarius Mts., Arizona, 122.
Eureka Mining District: See Arizona-Yavapai Co., 23.
Eureka Mining District: See New Mexico-Grant Co., 69.

F

Fairview: See Nevada-Churchill Co., 106.
Farmington: See New Mexico-San Juan Co., 99.
Flagstaff: See Arizona-Coconino Co., 116.
Foster claim: See New Mexico-Grant Co., 57.
Four Corners area: See Arizona-Apache Co., 17.
Four Corners area: See New Mexico-San Juan Co., 172.
Fred Sitton property: See Arizona-Apache Co., 153.
Fredonia: See Arizona-Coconino Co., 17.
Fridlund claim: See New Mexico-Rio Arriba Co., 35.
Fridlund dike: See New Mexico-Rio Arriba Co., 69.
Fridlund mine: See New Mexico-Rio Arriba Co., 42.
Frigita Peak: See Arizona-Santa Cruz Co., 103.

G

Galisteo monocline: See New Mexico-Santa Fe Co., 69.
Gallinas Mining District: See New Mexico-Lincoln Co., 183.
Gallinas Mts.: See New Mexico-Lincoln Co., 8, 76, 179.
Glen claims: See Arizona-Pima Co., 103.
Globe: See Arizona-Gila Co., 17, 41.
Globe (mine, pegmatite, etc.): See New Mexico-Rio Arriba Co.-Petaca Mining District, 100.
Glorieta: See New Mexico-Santa Fe Co., 66, 67, 69.
Golondrina claims: See Arizona-Graham Co., 103.
Goodsprings: See Nevada-Clark Co., 26, 37, 59, 126, 129.
Grants area: See New Mexico-McKinley Co., 29, 73, 77, 88, 176, 180, 182; New Mexico-Valencia Co., 29, 53, 88, 89, 165, 170, 172, 173, 174, 175, 180.
Green Monster mine: See Nevada-Clark Co., 129.
Grissom claim: See New Mexico-Grant Co., 57.

H

Hackberry: See Arizona-Mohave Co., 108, 109.
Hack's Canyon: See Arizona-Coconino Co., 15, 16, 17.
Hanover: See New Mexico-Grant Co., 45.
Happy Jack mine: See Arizona-Santa Cruz Co., 7, 81, 82, 103.
Harding mine: See New Mexico-Taos Co., 64, 69, 98, 141.
Harding pegmatite: See New Mexico-Taos Co., 65.
Harshaw Mining District: See Arizona-Santa Cruz Co., 81.
Haystack Mt.: See New Mexico-McKinley Co., 180.
Haystack Mountain Development Co.: See New Mexico-Valencia Co., 177.
Heneberg property: See Nevada-Nye Co., 131, 132, 137, 158.
Hillside mine: See Arizona-Yavapai Co., 3, 17, 83, 103, 138, 151.
Holbrook: See Arizona-Navajo Co., 144.
"Howard" claim: See Arizona-Cochise Co., 103.
Humdinger claim: See Nevada-Clark Co., 37.

I

Iris claims: See Arizona-Pima Co., 103.

J

Jerome: See Arizona-Yavapai Co., 2, 23.
Jerome Copper mine: See New Mexico-Socorro Co., 40, 60.
Jim Kane mine: See Arizona-Mohave Co., 103.
J. M. Pope's claims: See Arizona-Pima Co., 110.

K

Kate No. 3 claim: See Arizona-Pinal Co., 103.
Kayenta area: See Arizona-Navajo Co., 7, 72.
Kingman: See Arizona-Mohave Co., 17, 30, 103.
Kingman Feldspar mine: See Arizona-Mohave Co. 2, 23, 24.
Kinusta Mesa: See Arizona-Apache Co., 52.
Kithil, Camp: See New Mexico-Grant Co., 111, 112.

L

Laguna Indian Reservation: See New Mexico-Valencia Co., 170, 177, 180, 181.
Lake View claim: See Nevada-Clark Co., 37.
Lake View No. 1 claim: See Nevada-Clark Co., 37.
Las Tablas: See New Mexico-Rio Arriba Co., 19, 40, 69.

Las Vegas area: See New Mexico-San Miguel Co., 68, 69.
Leach claims: See New Mexico-Grant Co., 113.
Lee's Ferry: See Arizona-Coconino Co., 21.
Lena claims: See Arizona-Pima Co., 103.
Limitar Mts.: See New Mexico-Socorro Co., 40.
Lobato mine: See New Mexico-Rio Arriba Co., 19, 69.
Los Cerillos: See New Mexico-Santa Fe Co., 11.
Lucky Bill mine: See New Mexico-Grant Co., 114.
Lukachukai Basin: See Arizona-Apache Co., 150, 166.
Lukachukai District: See Lukachukai Mts., Arizona-Apache Co., 51.
Lukachukai Mts.: See Arizona-Apache Co., 51, 63, 77, 153, 167, 169, 185.
Lukachukai Mts.: See New Mexico-San Juan Co., 185, 186.

Mc

McElmo laterite: See Arizona-Navajo Co., 72.

M

Magma mine: See Arizona-Pinal Co., 45.
Majuba Hill: See Nevada-Pershing Co., 84.
Marble Canyon: See Arizona-Coconino Co., 21.
Memphis King mine: See New Mexico-Dona Ana Co., 160.
Mercer-King Consolidated Mines, Ltd.: See Arizona-Gila Co., 125.
Merry Widow claim: See New Mexico-Grant Co., 28, 57.
Merry Widow mine: See New Mexico-Grant Co., 112, 127.
Mesa Four-and-a-Half: See Arizona-Apache Co., 51.
Mesa V: See Arizona-Apache Co., 51.
Miami Mining District: See Arizona-Gila Co., 2, 24.
Midas: See Nevada-Elko Co., 156.
Middle Rio Grande Valley: See New Mexico, 74, 75.
Miller mine: See New Mexico-Rio Arriba Co., 42.
Mohave Mts.: See Arizona-Mohave Co., 2, 23, 24, 31.
Mohawk property: See Nevada-Esmeralda Co., 171.
Monument Valley: See Arizona-Navajo Co., 2, 7, 23, 24.
Morrison formation: See Arizona-General, 22. See Colorado Plateau, 22. See New Mexico-General, 22; New Mexico-McKinley Co., 77; New Mexico-Valencia Co., 89.
Morrison (McElmo) sandstone: See Arizona-Apache Co., 23.
Morristown: See Arizona-Maricopa Co., 17.
Muggins Mts.: See Arizona-Yuma Co., 97.

N

Natalia claims: See Arizona-Pima Co., 103.
Navajo Bridge: See Arizona-Coconino Co., 21.
Navajo Country: See Arizona-Navajo Co., 72.
Navajo Indian Reservation: See Arizona-Apache Co., 1, 7, 16, 41, 63, 78, 82, 87, 108, 109, 140, 144, 147, 149, 150, 161, 164, 166, 167, 169, 178, 184, 185.
Navajo Indian Reservation: See Arizona-Navajo Co., 178, 184.
Navajo Indian Reservation: See New Mexico-San Juan Co., 87, 140, 161, 172, 178, 185, 186.
North Star mine: See Nevada-Nye Co., 135.
Nunn claim: See Nevada-Clark Co., 37.

O

Oatman Route, Kingman: See Arizona-Mohave Co., 17.
Octave: See Arizona-Yavapai Co., 119.
Old Gold No. 1 claim: See Arizona-Santa Cruz Co., 103.
Oljeto: See Arizona-Navajo Co., 72.
Operation Haystack: See New Mexico-Valencia Co., 170.
Organ: See New Mexico-Dona Ana Co., 160.
Organ Mining District: See New Mexico-Dona Ana Co., 69.
Oro Blanco Mining District: See Arizona-Santa Cruz Co., 103.
Otto Forester's radium mine: See New Mexico-Grant Co., 19.

P

Palisade: See Nevada-Eureka Co., 26.
Papago Chief mine: See Arizona-Pima Co., 103, 152.
Papago Mining District: See Arizona-Pima Co., 103.
Parker Creek Canyon: See Arizona-Gila Co., 43.
Patterson Mining District: See Nevada-Lincoln Co., 80.
Peralta Canyon: See New Mexico-Sandoval Co., 40, 60, 69.
Peraulta Canyon: See Peralta Canyon, 69.
Petaca: See New Mexico-Rio Arriba Co., 19, 35, 69, 92.
Petaca Mining District: See New Mexico-Rio Arriba Co., 19, 40, 42, 54, 66, 69, 70, 100.
Phelps Dodge camp at Tyrone: See New Mexico-Grant Co., 56.
Pidlite pegmatite: See New Mexico-Mora Co., 70.
Pinon Range: See Nevada-Eureka Co., 26.
Pioche: See Nevada-Lincoln Co., 34, 82.
Pipe Springs National Monument: See Arizona-Mohave Co., 21.
Pittsburg Mining District: See New Mexico-Sierra Co., 69.
Polvadera Hills: See New Mexico-Socorro Co., 50.
Pope's claims: See Arizona-Pima Co., 110.
Prescott: See Arizona-Yavapai Co., 168.
President mine: See New Mexico-Colfax Co., 104.
Prewitt: See New Mexico-McKinley Co., 63, 180.
Prince of Arizona mine: See Arizona-Maricopa Co., 94.

Q–R

Radium: See Arizona-Gila Co., 125.
Radium Hot Springs: See Arizona-Yuma Co., 97.
Rainbow claims: See Nevada-Nye Co.-Heneberg property, 137, 143.
Rainbow claims: See Arizona-Mohave Co.-W. of Pipe Springs National Monument, 21.
Ra-Tor Mining and Manufacturing Co. claims: See New Mexico-Grant Co., 121.
Ra-Tor-Plac claims: See New Mexico-Grant Co., 56.
Ray's camp area: See Arizona-Maricopa Co., 36, 38.
Recapture sandstone: See New Mexico-Valencia Co., 53.
Red Bluff claims: See Arizona-Gila Co., 103.

Red Bluff Prospect: See Arizona-Gila Co., 43.
Red Cloud Canyon: See New Mexico-Lincoln Co., 76.
Red Cloud mine: See New Mexico-Lincoln Co., 8, 76.
Red Cloud prospect: See New Mexico-Lincoln Co., 76.
Red Hills claims: See Arizona-Mohave Co., 103.
Red Rock: See Arizona-Apache Co., 51, 52, 144, 166.
Rich Hill: See Arizona-Yavapai Co., 119.
Rink claim: See Nevada-Lyon Co., 128.
Rio Grande River sands: See New Mexico-Valencia Co., 75.
Rio Grande Valley, Middle: See New Mexico, 74, 75.
Rocky Canyon: See Nevada-Humboldt Co., 188.
Roosevelt Dam area: See Arizona-Gila Co., 43.
Rough Mt.: See New Mexico-Lincoln Co., 8, 76.
Round Mt.: See Nevada-Nye Co., 131, 132, 133, 134, 135, 137, 143, 157, 158.
Ruby: See Arizona-Santa Cruz Co., 101.
Ruby Mining District: See Arizona-Santa Cruz Co., 103.

S

St. Joe claims: See Arizona-Pima Co., 103.
Salt Wash, Morrison fm.: See Arizona-Apache Co., 51, 52, 63.
San Acacia: See New Mexico-Socorro Co., 50.
San Lorenzo Gulch: See New Mexico-Socorro Co., 50.
San Lorenzo Mining District: See New Mexico-Socorro Co., 40, 54, 69.
Santa Fe Railway land near Grants: See New Mexico-McKinley Co., 73, 176, 180; New Mexico-Valencia Co., 165, 172, 173, 174, 175, 177.
Scholle: See New Mexico-Socorro Co., 54, 69, 93, 99.
7-U-7 Ranch: See Arizona-Yavapai Co., 2, 23, 24.
Shamrock claim: See New Mexico-Grant Co., 57.
Shandon: See New Mexico-Sierra Co., 11, 78, 82.
Shinarump conglomerate: See Arizona-General, 22.
Shinarump conglomerate: See Colorado Plateau, 22.
Shinarump sandstone: See Arizona-Navajo Co., 23.
Shiprock: See New Mexico-San Juan Co., 47, 161, 182, 185, 186.
Sieber claim: See Nevada-Clark Co., 37.
Sierra Ancha: See Arizona-Gila Co., 43.
Sierrita Mts.: See Arizona-Pima Co., 103.
Signal City: See New Mexico-Grant Co., 93.
Silver City: See New Mexico-Grant Co., 99, 111, 115, 127, 159.
Sitton, Fred, property: See Arizona-Apache Co., 153.
Slaughter's mine: See Arizona-Yavapai Co., 105.
Sloan: See Nevada-Clark Co., 26, 34, 37, 59, 126.
Sloan Mining District: See Nevada-Clark Co., 59, 126.
"Spelbrink" claim: See Arizona-Santa Cruz Co., 103.
Superior: See Arizona-Pinal Co., 45.
Sutor: See Nevada-Clark Co., 26, 37, 59, 126.
Sutor Mining District: See Nevada-Clark Co., 59, 126.
Sylvanite Mining District: See New Mexico-Hidalgo Co., 69.

T

Taos: See New Mexico-Taos Co., 67.
Todilto limestone: See New Mexico-McKinley Co., 29, 77, 176: New Mexico-Valencia Co., 53, 89, 173.
Tombstone Mining District: See Arizona-Cochise Co., 1, 2, 6, 7, 23, 24.
Tonopah: See Nevada-Nye Co., 133, 134, 135, 157.
Topock: See Arizona-Mohave Co., 2, 23, 24, 31.
Tree Mesa: See Arizona-Apache Co.-Kinusta Mesa, 52.
Treloar's claims: See Arizona-Maricopa Co., 36, 38.
Tuer: See New Mexico-Santa Fe Co., 69.
Tullock mine: See New Mexico-Grant Co., 57.
Tyrone: See New Mexico-Grant Co., 33, 56, 57, 58, 121.

U–V

V.C.A. operations, Navajo Indian Reservation: See Arizona-Apache Co., 149.
Valley View claim: See Arizona-Cochise Co., 103.
Vanadinite Group: See Arizona-Gila Co., 41.
Vermillion Cliffs: See Arizona-Coconino Co., 16, 142, 144, 146.
Virgin Valley: See Nevada-Humboldt Co., 85.
Vulture Mts.: See Arizona-Maricopa Co., 2, 23, 24, 34, 36, 38.

W

Warm Creek Canyon: See Arizona-Gila Co., 43.
White Oaks District (should read: White Signal): See New Mexico-Grant Co., 33.
White Signal: See New Mexico-Grant Co., 19, 113
White Signal Mining District: See New Mexico-Grant Co., 19, 28, 54, 55, 57, 58, 69, 92, 93, 99, 102, 112, 113, 115, 127.
W. H. Slaughter's mine: See Arizona-Yavapai Co., 105.
Willabelle claim: See Nevada-Clark Co., 37.
Willow Creek: See New Mexico-San Miguel Co., 69.
Wonder: See Nevada-Churchill Co., 106.
Wrightson Mining District: See Arizona-Santa Cruz Co., 7, 81, 82.

X–Y

Yarnell Hill area: See Arizona-Yavapai Co., 23, 24.
Yellow Pine Mining District: See Nevada-Clark Co., 59, 126.
Yerington: See Nevada-Lyon Co., 128.

Z

Zuni Uplift: See New Mexico-McKinley Co., 20, 63.

Index II

Geographical Index for Arizona, Nevada, and New Mexico

(Numbers refer to References Listed in Bibliography)

ARIZONA

General

Carnotite Occurrences—
General: 7
(in) Morrison fm.: 22.

(in) Petrified wood: 148.
(in) Sandstone: 46.
(in) Shinarump conglomerate: 22.
Northeast part: 14.
Petrified Wood, Uranium-bearing, Occurrences—
General: carnotite: 148.
Thorium Occurrences—
General: 12, 25.
Torbernite Occurrences—
Northwest part: 14
Uranium Occurrences—
General: 12, 13, 25, 48.
Carnotite: 7
Carnotite in petrified wood: 148.
Carnotite in sandstone deposits: 46, 62.
Clare Pearson property: ore samples carry up to 10% uranium: 144
Copper-uranium deposits: 62.
First commercial deposit in state: 148.
Hydrothermal vein deposits: 62.
Northeast part: carnotite: 14.
Northwest part: inaccessible deposit with 1.5% uranium in ore; not to be developed: 136; torbernite: 14.
Possible occurrences: 71.
Uranium Production—
Uranium sold, subject to State Sales Tax: 145.
Uranium Prospecting—
General: 90, 124.

Andersonite Occurrences
See under individual county names and under Index III, Andersonite Occurrences—Arizona.

Apache County
Carnotite Occurrences—
Navajo Indian Reservation:—
General: 1, 16, 41, 78, 82, 108, 109, 147, 150, 161, 166.
Carrizo Mts.: 7, 86, 87.
West of: 2, 23, 24.
Claims subleased to V.C.A. by A.E.C.: 140
Four Corners area: 17.
Lukachukai Basin S. of Red Rock: 166.
Lukachukai Mts.: 63, 167.
Mesa Four-and-a-Half: 51.
Mesa V, 10 mi. W. of Red Rock, in Salt Wash, Morrison fm.: 51.
Limestones, Uranium-bearing, Occurrences—
Navajo Indian Reservation: 164.
Uranium Development—
Navajo Indian Reservation:—Lukachukai Mts.: mining recommendations: 169; ore reserves developed: 169.
Uranium Exploration—
Navajo Indian Reservation:
drilling program for 1951: 144
Uranium Occurrences—
Navajo Indian Reservation:—
General: carnotite: 1, 16, 41, 78, 82, 108, 109, 140, 147, 150, 161, 166.
Claims subleased to V.C.A. by A.E.C.: 140.
Navajos may reassign uranium mining rights: 178.
Uranium in limestone: 164.
Uranium production: 184.
V.C.A. operations, 200 t. uranium ore daily: 149.
Carrizo, 3 mi. W. of: uranium: 144; 12 mi. W. of: uranium: 144.
Carrizo Mts.: carnotite: 7, 86, 87; geology: 52; mineralization: 52; uranium & vanadium oxides in Salt Wash: 52.
West of: carnotite: 2, 24; carnotite in Morrison (McElmo) sandstone: 23.
Cove Mesa: geology: 52; mineralization: 52; uranium & vanadium oxides in Salt Wash: 52.
Cove Mesa, 14 mi. W. of Red Rock: uranium: 144.
Kinusta (Tree) Mesa: geology: 52; mineralization: 52; uranium & vanadium oxides in Salt Wash: 52.
Red Rock District: geology: 52; mineralization: 52; uranium & vanadium oxides in Salt Wash: 52.
Four Corners area:
carnotite: 17.
Lukachukai Basin:
uranium deposits: 150.
South of Red Rock: carnotite: 166.
Lukachukai Mts.: carnotite: 63, 167; new uranium discoveries: 77; uranium: 169.
Fred Sitton property: uranium deposit: 153.
Mesa Four-and-a-Half: carnotite: 51.
Mesa V, 10 mi. W. of Red Rock: carnotite and vanadium minerals in Salt Wash, Morrison fm.: 51; geology: 51.
Red Rock, 5 mi. N. of: uranium: 144.
Salt Wash, Morrison fm.: carnotite: 51.
Unnamed location 23 mi. S. of Mexican Hat, Utah: uranium: 144.
Uranium Prices—
Navajo Indian Reservation carnotites: percentage to Navajo owners: 140.
Uranium Processes—
Navajo Indian Reservation:
mill may be built: 164.
Navajo Indian Reservation carnotites, treatment: Durango, Colorado, plant when rehabilitated by V.C.A.: 140; White Canyon District, Utah, pilot treatment plant: 140.
Uranium Production—
Navajo Indian Reservation:
Five mines in operation: 147.
Mill may be built: 164.
Increase in 1951: 184.
200 t. carnotite ore per day: 147.
200 t. uranium ore mined daily: 144.
V.C.A. operations, 200 t. uranium ore daily: 149.
Uranium Prospecting—
Carrizo Mts.: diamond drilling: 154.

Bayleyite Occurrences
See under individual county names and under Index III, Bayleyite Occurrences—Arizona.

Bibliographies
Carnotite Occurrences: 61, 96.
Monazite Occurrences: 96.
Thorium Occurrences: 9, 96.
Uranium Occurrences: 9, 10, 61, 96.

ARIZONA (contd.)

Carnotite Occurrences
See under individual county names and under Index III, Carnotite Occurrences—Arizona
Bibliography: 61, 96.

Chevkinite Occurrences
See under individual county names and under Index III, Chevkinite Occurrences—Arizona.

Clays, Uranium-bearing, Occurrences
See under individual county names and under Index III, Clays, Uranium-bearing, Occurrences—Arizona.

Cochise County
Carnotite Occurrences—
Tombstone Mining District: 1, 7.
Meta-torbernite Occurrences—
"Howard" claim: 103.
Thorium Occurrences—
Tombstone Mining District:
allanite: 2, 23, 24;
allanite in granodiorite: 6.
Tyuyamunite Occurrences—
Bisbee: 2, 23, 24, 34.
Uranium Occurrences—
Bisbee: tyuyamunite: 2, 23, 24, 34.
"Howard" claim: meta-torbernite in quartz-wolframite veins: 103.
Tombstone Mining District: carnotite: 1, 7.
Valley View claim: uranium oxide: 103.

Coconino County
Carnotite Occurrences—
Hack's Canyon near Fredonia: carnotite to be developed: 17; carnotite to be treated at Marysvale, Utah, plant: 17.
Vermillion Cliffs, in petrified wood: 146; 3% uranium: 142.
Copper-Uranium Deposits—
Hack's Canyon: in copper mine: 15; metallurgy under study: 16.
Navajo Bridge, E. &. N. of: 21.
Petrified Wood, Uranium-bearing—
Lee's Ferry: 21.
Marble Canyon: 21.
Vermillion Cliffs: 16, 144; carnotite: 142, 146.
Uranium Occurrences—
Flagstaff, N. of: uranium oxide content, 1.5%: 116.
Hack's Canyon: copper-uranium ores in copper mine: 15; copper-uranium ores, metallurgy under study: 16.
Hack's Canyon near Fredonia: carnotite to be developed: 17; carnotite to be treated at Marysvale, Utah, plant: 17.
Lee's Ferry: uranium in petrified wood: 21.
Marble Canyon: uranium in petrified wood: 21.
Navajo Bridge, E. &. N. of: copper-uranium deposits: 21.
Vermillion Cliffs: carnotite in petrified wood: 146; 3% uranium: 142; uranium in petrified wood: 16, 144.
Uranium Production—
Flagstaff: uranium oxide concentrates: 116.
Vermillion Cliffs: ore ready for shipment: 144.

Colorado Plateau Section
General: carnotite: 63

Copper-Uranium Deposits
See under individual county names and under Index III, Copper-Uranium Deposits—Arizona.

Euxenite Occurrences
See under individual county names and under Index III, Euxenite Occurrences—Arizona.

Fergusonite Occurrences
See under individual county names and under Index III, Fergusonite Occurrences—Arizona.

Gila County
Carnotite Occurrences—
Mercer-King Consolidated Mines, Ltd., near Radium: 125.
Vanadinite Group of claims, 3 mi. N. of globe: 41.
Quartzite, Uranium-bearing, Occurrences—
Red Bluff Prospect:
Dripping Springs quartzite: 43.
Radioactive Quartzite—
Globe, 35 mi. N. of : 17.
Radioactive Rocks—
Dripping Springs quartzite: 43.
Globe, 35 mi. N. of: radioactive quartzite found by the Carl Larsons: 17.
Torbernite Occurrences—
Castle Dome mine, Miami Mining District: 2, 24.
Uranium Development—
Mercer-King Consolidated Mines, Ltd., near Radium: concentration plant to be built in six mos. if development is profitable: 125; shafts and tunnels to be developed: 125.
Uranium Occurrences—
Castle Dome mine, Miami Mining District: torbernite: 2, 24.
Mercer-King Consolidated Mines, Ltd., near Radium: carnotite: 125.
Red Bluff claims: secondary uranium minerals: 103.
Red Bluff Prospect in S. end of Sierra Ancha, 12 mi. N.E. of Roosevelt Dam: geology: 43; mineralogy: 43; structure: 43; stratigraphy: 43; uranium in Dripping Springs quartzite: 43.
Parker Creek Canyon: uranium in Dripping Springs quartzite: 43.
Warm Creek Canyon: uranium in Dripping Springs quartzite: 43.
Vanadinite Group of claims, 3 mi. N. of Globe: carnotite: 41.

Graham County
Pyromorphite, Uranium-bearing, Occurrences—
Golondrina claims: 103.
Uranium Occurrences—
Golondrina claims: uranium in pyromorphite: 103.

Kasolite Occurrences
See under individual county names and under Index III, Kasolite Occurrences—Arizona.

Laterites, Uranium-bearing, Occurrences
See under individual county names and under Index III, Laterites, Uranium-bearing, Occurrences—Arizona.

Limestones, Uranium-bearing, Occurrences
See under individual county names and under Index III, Limestones, Uranium-bearing, Occurrences—Arizona.

Maricopa County
Carnotite Occurrences
Aguila: 120.
Vulture Mts. S. of Aguila: 2, 23, 24, 34; Genesis, obscure: 38; Geology: 38; Mineralogy: 38.
Ray's camp area near Aguila: 36; 2 pits S.E. of, in volcanic tuffs: 38.
Treloar's claims near Aguila: 36; 5 mi. N.E. of Aguila, in volcanic tuffs: 38.
Microlite Occurrences—
Morristown, E. of: 17.
Uranium Occurrences—
Aguila: carnotite: 120.
Morristown, E. of: microlite, produced by Anderson Bros.: 17.
Prince of Arizona mine, 8 mi. N. of Beardsley station & 31 mi. N.W. of Phoenix: uranium oxides: 94.
Vulture Mts. S. of Aguila: carnotite: 2, 24, 34; carnotite in tuff: 23.
Ray's camp area near Aguila: carnotite in tuffs: 36; 2 pits S.E. of: carnotite in volcanic tuffs: 38.
Treloar's claims near Aguila: carnotite: 36; 5 mi. N.E. of Aguila: carnotite in volcanic tuffs: 38.
Uranium Production—
Morristown: microlite produced: 17.

Meta-torbernite Occurrences
See under individual county names and under Index III, Meta-torbernite Occurrences—Arizona.

Microlite Occurrences
See under individual county names and under Index III, Microlite Occurrences—Arizona.

Mohave County
Chevkinite Occurrences—
Aquarius Mts.: 2, 24, 44.
Clays, Uranium-bearing, Occurrences—
Aquarius Mts.: euxenite: 122.
Copper-Uranium Deposits—
Rainbow claims W. of Pipe Springs National Monument: 21.
Euxenite Occurrences—
Aquarius Mts., in clay: 122.
Big Sandy River, E. of, S. of Burro Creek: 2, 23, 24.
Kingman Feldspar mine, Cerbat Range: 2, 23, 24.
Fergusonite Occurrences—
Oatman Route, Kingman: 17.
Monazite Occurrences—
Aquarius Mts.: 2, 24, 44.
Chemehuevis Mining District, Mohave Mts., 20 mi. S.E. of Topock: 2, 23, 24, 31.
Pitchblende Occurrences—
Jim Kane mine N. W. of Kingman: 103.
Samarskite Occurrences—
Aquarius Mts.: 2, 23, 24, 44.
Kingman, N.E. of: 17.
Thorium Occurrences—
Aquarius Mts.: allanite, chevkinite, gadolinite, monazite, samarskite: 2, 24, 44; allanite, gadolinite in pegmatites, samarskite: 23.
Big Sandy River, E. of, S. of Burro Creek: euxenite: 2, 23, 24.
Chemehuevis Mining District, Mohave Mts., 20 mi. S.E. of Topock: monazite: 2, 23, 24; monazite in stream gravels: 31.
Hackberry, 20 mi. S. of: gadolinite in pegmatite: 108, 109.
Kingman: gadolinite: 30.
Kingman, N.E. of: samarskite: 17.
Kingman Feldspar mine, Cerbat Range: allanite, euxenite: 2; allanite in pegmatite, euxenite, gadolinite: 23; euxenite, gadolinite: 24.
North part: gadolinite in sand dunes: 24.
Oatman Route, Kingman: fergusonite: 17.
Uranium Occurrences—
Aquarius Mts.: allanite, chevkinite, gadolinite, monazite, samarskite: 2; euxenite in clay: 122: samarskite: 23, 24.
Big Ledge claims S.E. of Kingman, Cottonwood Mts.: uranium in red jasper: 103.
Big Sandy River, E. of, S. of Burro Creek: euxenite: 2.
Jim Kane mine N.W. of Kingman: pitchblende: 103.
Kingman Feldspar mine, Cerbat Range: allanite, euxenite: 2.
Kingman, N. E. of: samarskite, produced in commercial quantities: 17.
Oatman Route, Kingman: fergusonite, mined & concentrated by L. L. Edgerton: 17.
Rainbow claims W. of Pipe Springs National Monument: copper-uranium deposits: 21.
Red Hills claims: secondary uranium minerals: 103.
Uranium Production—
Kingman: samarskite in commercial quantities; fergusonite mined and concentrated: 17.

Monazite Occurrences
See under individual county names and under Index III, Monazite Occurrences—Arizona.
Bibliography: 96.

Navajo County
Carnotite Occurrences—
Kayenta area: 7.
Monument Valley: 2, 7, 23, 24.
Laterites, Uranium-bearing, Occurrences—
Oljeto N. of Kayenta: 72.
Petrified Wood, Uranium-bearing, Occurrences—
Holbrook, S. of: 144.
Uranium Occurrences—
Holbrook, S. of: 31 uranium claims: 144; uranium content of ore, 4–5%: 144; uranium in petrified wood in Chinle fm.: 144.
Kayenta area: carnotite: 7.

ARIZONA (contd.)
Monument Valley: carnotite: 2, 7, 24; carnotite in Shinarump sandstone: 23.
Navajo Indian Reservation: uranium production: 184.
Oljeto N. of Kayenta:
uranium in laterite of McElmo age: 72.
Uranium Production—
Navajo Indian Reservation: increase in 1951: 184.

Petrified Wood, Uranium-bearing, Occurrences
See under individual county names and under Index III, Petrified Wood, Uranium-bearing, Occurrences—Arizona

Pima County
Kasolite Occurrences—
Iris claims: 103.
Lena claims: 103.
St. Joe claims: 103.
Meta-torbernite Occurrences—
Papago Chief mine: 103.
Pitchblende Occurrences—
Ajo Mining District:—
J. M. Pope's seven claims, samples analyzed: 110.
Lena claims: 103.
Uraninite Occurrences—
Black Dike claims: 103.
Uranium Occurrences—
Ajo Mining District:—
J. M. Pope's seven claims: pitchblende, samples analyzed: 110.
Black Dike claims: uraninite: 103.
Glen claims: uranium in granite: 103.
Iris claims: kasolite: 103.
Lena claims: kasolite, pitchblende; 103.
Natalia claims: uranium deposit: 103.
Papago Chief mine, 65 mi. from Tucson: meta-torbernite, uranium-bearing salts: 103 uranium: 152.
Papago Mining District:—
Banner mine: uranium oxide: 103.
St. Joe claims: kasolite, uranophane: 103.
Sierrita Mts.: uranium deposit: 103.
Unnamed location in mountains: uranium boro-silicate, chemical analysis: 91.
Uranophane Occurrences—
St. Joe claims: 103.

Pinal County
Pitchblende Occurrences—
Kate No. 3 claim: 103.
Radioactive Areas—
Magma mine, Superior: sulphide minerals: 45.
Uranium Occurrences—
Kate No. 3 claim: pitchblende: 103

Pitchblende Occurrences
See under individual county names and under Index III, Pitchblende Occurrences—Arizona.

Pyromorphite, Uranium-bearing, Occurrences
See under individual county names and under Index III, Pyromorphite, Uranium-bearing, Occurrences—Arizona.

Quartzite, Uranium-bearing, Occurrences
See under individual county names and under Index III, Quartzite, Uranium-bearing, Occurrences—Arizona.

Radioactive Areas
See under individual county names and under Index III, Radioactive Areas—Arizona.

Radioactive Quartzite
See under individual county names and under Index III, Radioactive Quartzite—Arizona.

Radioactive Rocks
See under individual county names and under Index III, Radioactive Rocks—Arizona.

Radioactive Springs
See under individual county names and under Index III, Radioactive Springs—Arizona.

Samarskite Occurrences
See under individual county names and under Index III, Samarskite Occurrences—Arizona.

Santa Cruz County
Pitchblende Occurrences—
Annie Laurie claims: 103.
Annie Laurie prospect near Ruby: 103.
Wrightson Mining District:—
Happy Jack mine: 7, 103.
Pyromorphite, Uranium-bearing Occurrences—
"Spelbrink" claim: 103.
Uraninite Occurrences—
Harshaw Mining District: 81.
Wrightson Mining District:—
Happy Jack mine: 81, 82.
Uranium Occurrences—
Annie Laurie claims: pitchblende: 103.
Annie Laurie prospect near Ruby: geology: 101; mineralogy: 101; pitchblende: 101; prospecting work: 101; radiometric survey: 101.
Harshaw Mining District: uraninite: 81.
Old Gold No. 1 claim, S. of Annie Laurie claims: uranium oxide: 103.
Oro Blanco Mining District:—
Frigita Peak, W. side of: uranium oxide: 103.
Ruby Mining District:—
Dry Springs: uranium oxide: 103.
"Spelbrink" claim: uranium in radioactive pyromorphite: 103.
Wrightson Mining District:—
Happy Jack mine: pitchblende: 7, 103; uraninite: 81, 82.

Schroeckingerite Occurrences
See under individual county names and under Index III, Schroeckingerite Occurrences—Arizona.

Swartzite Occurrences
See under individual county names and under Index III, Swartzite Occurrences—Arizona.

Thorium Occurrences
See under individual county names and under Index III, Thorium Occurrences—Arizona.
Bibliography: 9, 96.

Torbernite Occurrences
See under individual county names and under Index III, Torbernite Occurrences—Arizona.

Tyuyamunite Occurrences
See under individual county names and under

Index III, Tyuyamunite Occurrences—Arizona.

Uraninite Occurrences
See under individual county names and under Index III, Uraninite Occurrences—Arizona.

Uranium Development
See under individual county names and under Index III, Uranium Development—Arizona.

Uranium Exploration
See under individual county names and under Index III, Uranium Exploration—Arizona.
Drilling Programs:
U.S.A.E.C. (by private contractors), methods and results: 18.
U.S.B.M., methods and results: 18.
U.S.G.S., methods and results: 18.

Uranium Occurrences
See under individual county names and under Index III, Uranium Occurrences—Arizona.
Bibliography: 9, 10, 61, 96.

Uranium Prices
See under individual county names and under Index III, Uranium Prices—Arizona.

Uranium Processes
See under individual county names and under Index III, Uranium Processes—Arizona.

Uranium Production
See under individual county names and under Index III, Uranium Production—Arizona.

Uranium Prospecting
See under individual county names and under Index III, Uranium Prospecting—Arizona.

Uranophane Occurrences
See under individual county names and under Index III, Uranophane Occurrences—Arizona.

Yavapai County
Andersonite Occurrences—
Hillside mine N. of Bagdad: 3, 103, 138, 151.
Bayleyite Occurrences—
Hillside mine N. of Bagdad: 3, 103, 138, 151.
Fergusonite Occurrences—
Yarnell Hill area: 23, 24.
Monazite Occurrences—
Black Canyon Creek:11.
Pitchblende Occurrences—
Hillside mine: 103.
W. H. Slaughter's mine near Columbia: 105.
Radioactive Springs—
Castle Hot Springs in foothills of Bradshaw Mts.: gas in water, quite radioactive: 5; no radium in water by chemical analysis: 5; water, radioactive: 5.
Samarskite Occurrences—
Black Hills near Jerome: 2, 23, 24.
Schroeckingerite Occurrences—
Hillside mine N. of Bagdad: 3, 138.
Swartzite Occurrences—
Hillside mine N. of Bagdad: 3, 103, 138, 151.
Thorium Occurrences—
Black Canyon Creek: monazite: 11.
Black Hills near Jerome: samarskite: 2, 23, 24.
Eureka Mining District on 7-U-7 Ranch near Bagdad: allanite: 2, 23, 24.
Yarnell Hill area: fergusonite: 23, 24.
Torbernite Occurrences—
Eureka Mining District on 7-U-7 Ranch near Bagdad: 2, 23, 24.
Uranium Occurrences—
Black Hills near Jerome: samarskite: 2, 23, 24.
Eureka Mining District on 7-U-7 Ranch near Bagdad: allanite, torbernite: 2, 23, 24.
Hillside mine N. of Bagdad: andersonite, bayleyite, swartzite: 151;
andersonite, bayleyite, pitchblende, swartzite: 103;
andersonite, bayleyite, schroeckingerite, swartzite: 3, 138;
uranium, metallurgical tests: 17;
uranium, mine development: 17;
uranium minerals: 83.
Mesa below Octave and Rich Hill: radium, platinum in black sand, samples analyzed: 119.
Prescott area, three locations: uranium deposits: 168.
W. H. Slaughter's mine near Columbia: pitchblende: 105.
Yarnell Hill area: fergusonite: 23, 24.
Uranium Production—
Prescott area: uranium shipments from three locations: 168.
Uranium Prospecting—
General: Smithsonian Institution's work: 124.

Yuma County
Radioactive Springs—
Radium Hot Springs near S.E. margin of Muggins Mts.: radium emanation in water: 97.

COLORADO PLATEAU

General
Carnotite Occurrences—
Morrison fm.: 22;
channel deposits: 22;
genesis: 22;
geology: 22;
ore deposits: 22;
uranium production: 22.
Shinarump conglomerate: 22.
Uranium Development—
General: 73.
Uranium Occurrences—
General: 48; carnotite in Entrada and Salt Wash formations: 63.
Carnotite Deposits:—
Arizona: 22.
Morrison fm.: 22.
New Mexico: 22.
Shinarump conglomerate: 22.
Uranium Prices—
U.S.A.E.C. Bonus: 163.
U.S.A.E.C. Bonus, minimum prices: 187.
Uranium Production—
U.S.A.E.C. Bonus, Increased by: 163.
Uranium Prospecting—
Diamond drilling in Arizona, Colorado, and Utah: 154.

COLORADO PLATEAU (contd.)

Carnotite Occurrences
See under General and under Index III, Carnotite Occurrences—Colorado Plateau.

Uranium Development
See under General and under Index III, Uranium Development—Colorado Plateau.

Uranium Exploration
Drilling Programs—
U.S.A.E.C. (by private contractors), methods and results: 18.
U.S.B.M., methods and results: 18.
U.S.G.S., methods and results: 18.

Uranium Occurrences
See under General and under Index III, Uranium Occurrences—Colorado Plateau.

Uranium Prices
See under General and under Index III, Uranium Prices—Colorado Plateau.

Uranium Production
See under General and under Index III, Uranium Production—Colorado Plateau.

Uranium Prospecting
See under General and under Index III, Uranium Prospecting—Colorado Plateau.

NAVAJO INDIAN RESERVATION

General
Uranium Exploration—
Navajo finders can claim ore: 77.
U.S.A.E.C. Training Program for Indians: 77.
Uranium Mining—
New regulations for non-Indians: 186.
Uranium Occurrences—
Arizona: Navajos may reassign uranium mining rights: 178.
Arizona, New Mexico, Utah: carnotite: 161.
New Mexico: Navajos may reassign uranium mining rights: 178.

NEVADA

General
Carnotite Occurrences
General: 117.
Lignites, Uranium-bearing, Occurrences—
General: 27.
Thorium Occurrences—
General: 12, 25.
Uranium Exploration—
General: tests by Uranium Vanadium Exploration Co.: 139.
Uranium Occurrences—
General: 12, 13, 25.
Carnotite: 117; in sandstone deposits: 62.
Copper-uranium deposits: 62.
Hydrothermal vein deposits: 62.
Lignites, Uranium-bearing: 27.
Tests by Uranium Vanadium Exploration Co.: 139.
Uranium Prospecting—
General: 90.
Smithsonian Institution's work: 124.

Asphaltites, Uranium-bearing, Occurrences
See under individual county names and under Index III, Asphaltites, Uranium-bearing, Occurrences—Nevada.

Autunite Occurrences
See under individual county names and under Index III, Autunite Occurrences—Nevada.

Bastnasite Occurrences
See under individual county names and under Index III, Bastnasite Occurrences—Nevada.

Bibliographies
Thorium Occurrences: 9.
Uranium Occurrences: 9, 10, 26.

Carnotite Occurrences
See under individual county names and under Index III, Carnotite Occurrences—Nevada.

Churchill County
Uranium Occurrences—
Wonder and Fairview, location between: uranium ore "of good grade": 106.

Clark County
Bastnasite Occurrences—
Clark Mt.: 162
Carnotite Occurrences—
Sloan Mining District:—
Sloan: 26, 34.
Sloan, 2 mi. S. of: 59, 126; in railroad cut: 37.
Sutor Mining District:—
Sutor, 2 mi. W. of: 126.
Sutor area: 59.
Humdinger claim: 37.
Lake View claim: 37.
Lake View No. 1 claim: 37.
Nunn claim: 37.
Sieber claim: 37.
Willabelle claim: 37.
Yellow Pine Mining District:—
Goodsprings: 126.
Goodsprings, 2 mi. N. of: 37, 59.
Thorium Occurrences—
Clark Mt.: bastnasite: 162.
Uranium Occurrences—
Green Monster mine near Goodsprings: uranium: 129; prospecting work to be started: 129.
Sloan Mining District:—
Sloan: carnotite: 26: carnotite in rhyolite joints: 34.
Sloan, 2 mi. S. of, in railroad cut: carnotite: 37.
Sloan, 2 mi. S. of:
carnotite: 126;
carnotite, coating joints in rhyolite: 59.
Sutor Mining District:—
Sutor: radium: 26;
carnotite: 126.
Sutor area: carnotite, patches with manganese oxide in sandstone: 59.
Humdinger claim: carnotite: 37.
Lake View claim: carnotite: 37.
Lake View No. 1 claim: carnotite: 37.
Nunn claim: carnotite: 37.
Sieber claim: carnotite: 37.
Willabelle claim: carnotite: 37.
Yellow Pine Mining District:—
Goodsprings: radium: 26; carnotite: 126.
Goodsprings, 2 mi. N. of: carnotite: 37; carnotite in sandstone: 59.

Uranium Prospecting—
Green Monster mine near Goodsprings: 129.

Clays, Uranium-bearing, Occurrences
See under individual county names and under Index III, Clays, Uranium-bearing, Occurrences—Nevada.

Elko County
Thorium Occurrences—
Contact District: allanite: 79.
Uranium Occurrences—
Midas: low-grade uranium ore: 156.

Esmeralda County
Radioactive Areas—
Mohawk property: radioactive mineral: 171.

Eureka County
Asphaltites, Uranium-bearing, Occurrences—
Unnamed location in Pinon Range, 15 mi. S. of Palisade: 26.
Uranium Occurrences—
Unnamed location in Pinon Range, 15 mi. S. of Palisade: uranium in asphaltite: 26.

Humboldt County
Carnotite Occurrences—
Virgin Valley, in opal: 85.
Opal, Uranium-bearing, Occurrences—
Virgin Valley: carnotite: 85.
Pitchblende Occurrences—
Rocky Canyon, vein being developed: 188.
Uranium Occurrences—
Rocky Canyon: pitchblende vein being developed: 188.
Virgin Valley: carnotite in opal: 85;
geology: 85;
mineralogy: 85;
ore deposits: 85;
radioactivity measurements: 85.
Uranium Production—
Rocky Canyon: pitchblende with 0.7% U_3O_8 to be shipped to Colorado Springs ore-buying station: 188.

Lignites, Uranium-bearing, Occurrences
See under individual county names and under Index III, Lignites, Uranium-bearing, Occurrences—Nevada.

Lincoln County
Carnotite Occurrences—
Atlanta Mining District: 59.
Atlanta mine: 37, 39, 82, 126.
Pioche: 34.
Clays, Uranium-bearing, Occurrences—
Patterson Mining District:—
Cave Valley cave: 80.
Uranium Occurrences—
Atlanta Mining District:—carnotite in rhyolite joints and in gold ore: 59; radium: 26;
Atlanta mine: carnotite: 37, 39, 82, 126.
Patterson Mining District:—
Cave Valley cave: trace of uranium in clay: 80.
Cave Valley mine: reported uranium and radioactivity not found: 80.
Cave Valley mine of Great Western Co., Caliente: uranium deposit: 123.
Pioche: carnotite in andesite: 34.
Pioche, 50 mi. N. of:
unidentified carnotite-like mineral: 82.

Lyon County
Pitchblende Occurrences—
Southern part: 155.
Radioactive Areas—
Rink claim, Cambridge Mining Co., near Yerington: radioactive deposits: 128.
Uranium Occurrences—
Southern part: pitchblende: 155.
Two unnamed locations: uranium deposits: 130.

Monazite Occurrences
See under individual county names and under Index III, Monazite Occurrences—Nevada.

Nye County
Autunite Occurrences—
Round Mt.:—
Tonopah, some 6–8% uranium ore: 157.
Torbernite Occurrences—
Round Mt.:—
Tonopah: 133, 134.
Uranium Development—
Round Mt.:—
Heneberg property (or Rainbow claims): uranium deposit, 137, 143; new development work: 158.
Tonopah: commercial uranium: 133.
Uranium Occurrences—
Round Mt.:—
Heneberg property (or Rainbow claims): uranium deposit: 131, 132; under development: 137, 143.
North Star mine at Tonopah: uranium deposit: 135.
Tonopah: autunite, some 6–8% uranium ore: 157; torbernite and "commercial" uranium: 133, 134.

Opal, Uranium-bearing, Occurrences
See under individual county names and under Index III, Opal, Uranium-bearing, Occurrences—Nevada.

Ormsby County
Monazite Occurrences—
Carson City: 11, 82; in black sands: 59, 78.
Thorium Occurrences—
Carson City: monazite: 11, 82; monazite in black sands: 59, 78.

Pershing County
Torbernite Occurrences—
Antelope Mining District:—
Majuba Hill: 84.
Uranium Occurrences—
Antelope Mining District:—
Majuba Hill: torbernite: 84.

Pitchblende Occurrences
See under individual county names and under Index III, Pitchblende Occurrences—Nevada.

Radioactive Areas
See under individual county names and under Index III, Radioactive Areas—Nevada.

Thorium Occurrences
See under individual county names and under Index III, Thorium Occurrences—Nevada.
Bibliography: 9.

NEVADA (contd.)

Torbernite Occurrences
See under individual county names and under Index III, Torbernite Occurrences—Nevada.

Uranium Development
See under individual county names and under Index III, Uranium Development—Nevada.

Uranium Exploration
See under individual county names and under Index III, Uranium Exploration—Nevada.

Uranium Occurrences
See under individual county names and under Index III, Uranium Occurrences—Nevada.
Bibliography: 9, 10, 26.

Uranium Production
See under individual county names and under Index III, Uranium Production—Nevada.

Uranium Prospecting
See under individual county names and under Index III, Uranium Prospecting—Nevada.

NEW MEXICO

General
Carnotite Occurrences—
General: in sandstone: 46.
Morrison fm.: 22.
Unnamed location, N.W. part of state: 93.
Fluorescent Minerals, Uranium-bearing, Occurrences—
Mineral headings: autunite, johannite, meta-torbernite, schroeckingerite, torbernite: 32.
Chemical formulae: 32.
Color under short and long rays: 32.
Fluorite, Uranium-bearing, Occurrences—
General: 95.
Lignites, Uranium-bearing, Occurrences—
General: 62.
Limestones, Uranium-bearing, Occurrences—
General: 27.
Monazite Occurrences—
General: 117.
Radioactive Minerals, Thorium-bearing, Occurrences—
Minerals named: fergusonite, gummite, hachettolite, microlite, pitchblende, samarskite, uraninite: 32.
Chemical formulae: 32.
Radioactive Minerals, Uranium-bearing, Occurrences—
Minerals named: autunite, bassetite, carnotite, cyrtolite, fergusonite, gummite, hachettolite, microlite, pitchblende, samarskite, torbernite, meta-torbernite, uraninite, uranophane: 32.
Chemical formulae: 32.
Thorium Occurrences—
General: 12, 25; monazite: 117.
Torbernite Occurrences—
General: 118.
Uranium Occurrences—
General: 12, 13, 25, 48.
Carnotite in sandstone: 46, 62.
Copper-uranium deposits: 62.
Fluorite, uranium-bearing: 95.
Hydrothermal vein deposits: 62.
Lignites, uranium-bearing: 62.
Limestones, uranium-bearing: 27.
Torbernite: 118.
Unnamed location, N.W. part of state: carnotite: 93.
Uranium Prospecting—
General: 90.

Autunite Occurrences
See under individual county names and under Index III, Autunite Occurrences—New Mexico.

Bastnasite Occurrences
See under individual county names and under Index III, Bastnasite Occurrences—New Mexico.

Bibliographies
Thorium Occurrences: 4, 9.
Uranium Occurrences: 4, 9, 10.

Carnotite Occurrences
See under individual county names and under Index III, Carnotite Occurrences—New Mexico.

Colfax County
Uraninite Occurrences—
President mine near Elizabethtown: 104.
Uranium Occurrences—
President mine near Elizabethtown: uraninite: 104.

Colorado Plateau Section
Uranium Occurrences—
General: carnotite: 63.

Copper-Uranium Deposits
See under individual county names and under Index III, Copper-Uranium Deposits—New Mexico.

Cyrtolite Occurrences
See under individual county names and under Index III, Cyrtolite Occurrences—New Mexico.

Dona Ana County
Monazite Occurrences—
Organ Mining District: 69.
Thorium Occurrences—
Organ Mining District: monazite: 69.
Uranium Occurrences—
Memphis King mine at Organ: secondary uranium mineral: 160.

Fergusonite Occurrences
See under individual county names and under Index III, Fergusonite Occurrences—New Mexico.

Fluorescent Minerals, Uranium-bearing, Occurrences
See under individual county names and under Index III, Fluorescent Minerals, Uranium-bearing, Occurrences—New Mexico.

Fluorite, Uranium-bearing, Occurrences
See under individual county names and under Index III, Fluorite, Uranium-bearing, Occurrences—New Mexico.

Grant County
Autunite Occurrences—
Big Burro Mt.:—
Ra-Tor-Plac Co.'s 3 claims, 10 mi. S. of Phelps Dodge camp at Tyrone: 56.
Eureka Mining District: (?) 69.

White Oaks (should read: White Signal) Mining District, 9 mi. S. of Tyrone: 33.
White Signal Mining District: 54, 69, 102.
Acme claim: 57.
Burro Mts., 4 mi. E. of, in diabase dikes: 55.
Foster claim: 57.
Grissom claim: 57.
Merry Widow claim: 57.
Shamrock claim: 57.
Tullock mine: 57.
Kithilite Occurrences—
White Signal Mining District:—
Camp Kithil near Silver City: 111.
Tyrone: 58.
Pitchblende Occurrences—
Black Hawk Mining District: 69.
White Signal Mining District:—
Black Hawk camp at Bullard's Peak, 12 mi. N.W. of Tyrone: 57.
Merry Widow mine at Silver City: 127.
Tyrone: 58.
Radioactive Areas—
Hanover: lead-zinc ore: 45.
Torbernite Occurrences—
Big Burro Mt.:—
Ra-Tor-Plac Co.'s 3 claims, 10 mi. S. of Phelps Dodge camp at Tyrone: 56.
White Oaks (should read: White Signal) Mining District, 9 mi. S. of Tyrone: 33.
White Signal Mining District: 54, 69, 102.
Acme claim: 57.
Burro Mts., 4 mi. E. of, in diabase dikes: 55.
Camp Kithil: 112.
Foster claim: 57.
Grissom claim: 57.
Merry Widow claim: 28, 57.
Merry Widow mine at Silver City: 127.
Otto Forester's radium mine, 1 mi. S. of White Signal post office: 19.
Shamrock claim: 57.
Signal City: 93.
Silver City: 99, 115.
Tullock mine: 57.
Tyrone: 58.
Uranium Development—
White Signal Mining District:—
Merry Widow mine at Silver City: shaft deepened: 127.
Tyrone: torbernite being mined: 58.
Uranium Occurrences—
Big Burro Mt.:—
Ra-Tor-Plac Co.'s 3 claims, 10 mi. S. of Phelps Dodge camp at Tyrone: autunite, torbernite in diabase dike walls: 56.
Ra-Tor Mining and Manufacturing Co. claims near Tyrone: uranium, radium: 121.
Black Hawk Mining District: pitchblende: 69.
Central Mining District:—
Lucky Bill mine at Bayard station: uranium oxide: 114.
Eureka Mining District: autunite (?): 69.
White Oaks (should read: White Signal) Mining District, 9 mi. S. of Tyrone: autunite, torbernite: 33.
White Signal Mining District: 92; autunite, torbernite: 54, 69, 102.
A. A. Leach claims near White Signal post office: 113.
Acme claim: autunite, torbernite: 57.
Black Hawk camp at Bullard's Peak, 12 mi. N.W. of Tyrone: pitchblende: 57.
Burro Mts., 4 mi. E. of: autunite, torbernite in diabase dikes: 55.
Camp Kithil: torbernite: 112.
Camp Kithil near Silver City: kithilite, a copperless torbernite: 111.
Foster claim: autunite, torbernite: 57.
Grissom claim: autunite, torbernite: 57.
Merry Widow claim: autunite, torbernite: 57; torbernite: 28; exploration work: 28; geology: 28.
Merry Widow mine at Silver City: pitchblende, torbernite: 127.
Merry Widow mine shaft: high grade uranium ore: 112.
Otto Forester's radium mine, 1 mi. S. of White Signal post office: torbernite in felsite dike: 19; torbernite ore worth $25 per ton: 19; plan to install concentrating mill: 19.
Shamrock claim, 8 mi. S. of Tyrone: autunite, torbernite: 57.
Uranium Occurrences—
White Signal Mining District:—
Signal City: torbernite: 93.
Silver City: torbernite: 99, 115.
Silver City, 2000 acres, 17 mi. from: uranium: 159.
Tullock mine, 8 mi. S. of Tyrone: autunite, torbernite: 57.
Tyrone: kithilite, pitchblende, torbernite: 58.
Uranium Production—
Big Burro Mt.:—
Ra-Tor-Plac Co.'s 3 claims, 10 mi. S. of Phelps Dodge camp at Tyrone: autunite, torbernite mined: 56; ore crushed and dry concentrated: 56; ore marketed as the Ra-Tor Plac for making water radioactive for medicinal use: 56.
Ra-Tor Mining and Manufacturing Co., Tyrone: ore mill: 121; ore mining: 121.
White Oaks (should read: White Signal) Mining District, 9 mi. S. of Tyrone: 33.
White Signal Mining District: 54.
Camp Kithil: torbernite mining stopped; too hard to process: 112.

Gummite Occurrences
See under individual county names and under Index III, Gummite Occurrences—New Mexico.

Hidalgo County
Autunite Occurrences—
Sylvanite Mining District: 69.
Uranium Occurrences—
Sylvanite Mining District: autunite: 69.

Kithilite Occurrences
See under individual county names and under Index III, Kithilite Occurrences—New Mexico.

Lignites, Uranium-bearing, Occurrences
See under individual county names and under Index III, Lignites, Uranium-bearing, Occurrences—New Mexico.

NEW MEXICO (contd.)

Limestones, Uranium-bearing, Occurrences
See under individual county names and under Index III, Limestones, Uranium-bearing, Occurrences—New Mexico.

Lincoln County
Bastnasite Occurrences—
Gallinas Mining District: 183.
Gallinas Mts.: 179.
All American prospect near head of Red Cloud Canyon: 76.
Eagle Nest claim No. 2, ¾ mi. N. of Red Cloud mine on SW-trending spur of Rough Mt.: occasional crystals with fluorite & barite: 8.
Eagle Nest prospect ¾ mi. N. of Red Cloud mine on SW-trending spur of Rough Mt.: 76.
Red Cloud prospect in Red Cloud Canyon: 76.
Thorium Occurrences—
Gallinas Mining District: bastnasite: 183; ore treatment: 183; production: 183.
Gallinas Mts.: bastnasite: 179.
Eagle Nest claim No. 2, ¾ mi. N. of Red Cloud mine on SW-trending spur of Rough Mt.: bastnasite: 8.
Red Cloud Canyon: bastnasite: 76.
Thorium Processes—
Gallinas Mts.: mill for processing bastnasite: 179.
Thorium Production—
Gallinas Mts.: bastnasite ore processed: 179.

McKinley County
Carnotite Occurrences—
Grants area:—
Santa Fe Railway land: 176.
Gummite Occurrences—
Grants area:—
Santa Fe Railway land: 176.
Limestones, Uranium-bearing, Occurrences—
Zuni Uplift: 20.
Pitchblende Occurrences—
Grants area:—
Santa Fe Railway land: 176.
Zuni Uplift area 5 mi. N. of Prewitt: 63.
Rutherfordine Occurrences—
Grants area:—
Santa Fe Railway land: 176.
Thorium Occurrences—
Grants area:—
Santa Fe Railway land: gummite, rutherfordine in Todilto limestone: 176.
Tyuyamunite Occurrences—
Grants Area:—
Santa Fe Railway land: 176.
Uranium Development—
Grants area: 88.
Santa Fe Railway land: 73; assays of samples: 176; development work: 176; test pitting: 176.
Uranium Occurrences—
Grants area: uranium deposits: 88; uranium in Todilto limestone: 29; development of uranium deposits in Todilto limestone and Brushy Basin member of Morrison fm.: 77.
Santa Fe Railway land: carnotite, gummite, pitchblende, rutherfordine, tyuyamunite, uranophane in Todilto limestone: 176; geology: 176; mineralization: 176.
Santa Fe Railway land, Haystack Mt., N. of Prewitt: uranium deposits: 180.
Zuni Uplift: uranium-bearing limestone: 20.
Zuni Uplift area 5 mi. N. of Prewitt: pitchblende and other minerals: 63.
Uranium Processes—
Grants area: Anaconda to build plant: 73.
Uranium Production—
Grants area: Anaconda to build processing plant: 182.
Uranophane Occurrences—
Grants area:—
Santa Fe Railway land: 176.

Microlite Occurrences
See under individual county names and under Index III, Microlite Occurrences—New Mexico.

Middle Rio Grande Valley
Monazite Occurrences—
Middle Rio Grande Valley: 74.
Valencia County:—
Bosque, 0.6%, or less in Rio Grande River sands: 75.
Thorium Occurrences—
Middle Rio Grande Valley: monazite: 74.
Valencia County:—
Bosque: Rio Grande River sands carrying 0.6%, or less, monazite: 75.

Monazite Occurrences—
See under individual county names and under Index III, Monazite Occurrences—New Mexico.
Mineralogy—
General: pilot analysis made of specimen: 67; specimens analyzed: 66.

Mora County
Microlite Occurrences—
Pidlite pegmatite: 70.
Uranium Occurrences—
Pidlite pegmatite: microlite: 70.

Pitchblende Occurrences
See under individual county names and under Index III, Pitchblende Occurrences—New Mexico.

Radioactive Areas
See under individual county names and under Index III, Radioactive Areas—New Mexico.

Radioactive Minerals, Thorium-bearing, Occurrences
See under individual county names and under Index III, Radioactive Minerals, Thorium-bearing, Occurrences—New Mexico.

Radioactive Minerals, Uranium-bearing, Occurrences
See under individual county names and under Index III, Radioactive Minerals, Uranium-bearing, Occurrences—New Mexico.

Radium Occurrences
See under individual county names and under Index III, Uranium Occurrences—New Mexico: 92.

Rio Arriba County
Fergusonite Occurrences—
Petaca Mining District:—
Fridlund dike, 2½ mi. S. of Petaca: 69.
Gummite Occurrences—
Petaca Mining District: 54.
Beryl Prospect N. of Cribbensville & S. of Canada la Jarita: 42.
Claim 2½ mi. S.W. of Petaca: 69.
Lignites, Uranium-bearing, Occurrences—
General: 53.
Monazite Occurrences—
Chama River: (?) 40, 69.
Petaca Mining District:—
Beryl Prospect N. of Cribbensville & S. of Canada la Jarita: 42.
Cribbenville mine, Petaca: 66, 69.
Fridlund claim, 2½ mi. S.W. of Petaca: 35.
Fridlund mine S. of Canada la Jarita: 42.
Globe mine: 100.
Globe pegmatite: 100.
Las Tablas: 19.
Miller mine S. of Canada la Jarita: 42.
Pitchblende Occurrences—
Petaca Mining District:—
Claim 2½ mi. S.W. of Petaca: 69.
Samarskite Occurrences—
Petaca Mining District: 54; in pegmatite: 70.
Beryl Prospect N. of Cribbensville & S. of Canada la Jarita: 42.
Fridlund claim, 2½ mi. S.W. of Petaca: 35.
Fridlund claim: genesis of specimen: 35; radiograph analysis of specimen: 35.
Fridlund dike, 2½ mi. S. of Petaca: 69.
Fridlund mine S. of Canada la Jarita: 42.
Globe mine: 100.
Globe pegmatite: 100.
Las Tablas: 40.
Lobato mine near Las Tablas: 19, 69.
Miller mine S. of Canada la Jarita: 42.
Thorium Occurrences—
Chama River: monazite in sand: (?) 40, 69.
Petaca Mining District: gummite, samarskite, uraninite, uranophane: 54; samarskite in pegmatite: 70.
Beryl Prospect N. of Cribbensville & S. of Canada la Jarita: gummite, monazite, samarskite, uraninite: 42.
Claim 2½ mi. S.W. of Petaca: gummite, pitchblende, uranophane: 69.
Cribbenville mine, Petaca: monazite with uranium: 66, 69.
Fridlund claim, 2½ mi. S.W. of Petaca: monazite, samarskite, uraninite: 35.
Fridlund dike, 2½ mi. S. of Petaca: fergusonite, samarskite, uraninite, etc.: 69.
Fridlund mine S. of Canada la Jarita: monazite, samarskite: 42.
Globe mine: monazite, samarskite: 100.
Globe pegmatite: monazite, samarskite 100;
geology: 100;
mineralization: 100;
mineralogy: 100;
structure: 100.
Las Tablas: monazite: 19;
samarskite, thorium, etc.: 40.
Lobato mine near Las Tablas: samarskite: 19, 69.
Miller mine S. of Canada la Jarita: monazite, samarskite: 42.
Uraninite Occurrences—
Petaca Mining District: 54.
Beryl Prospect N. of Cribbensville & S. of Canada la Jarita: 42.
Fridlund claim, 2½ mi. S.W. of Petaca: 35.
Fridlund dike, 2½ mi. S. of Petaca: 69.
Uranium Occurrences—
General: uranium-bearing lignites: 53.
Petaca Mining District: gummite, samarskite, uraninite, uranophane: 54; samarskite in pegmatite: 70.
Beryl Prospect N. of Cribbensville & S. of Canada la Jarita: gummite, monazite, samarskite, uraninite: 42.
Claim 2½ mi. S.W. of Petaca: gummite, pitchblende, uranophane: 69.
Cribbenville mine, Petaca: monazite with uranium: 66, 69.
Fridlund claim, 2½ mi. S.W. of Petaca: monazite, samarskite, uraninite: 35.
Fridlund dike, 2½ mi. S. of Petaca: fergusonite, samarskite, uraninite, etc.: 69.
Fridlund mine S. of Canada la Jarita: monazite, samarskite: 42.
Globe mine: monazite, samarskite: 100.
Globe pegmatite: monazite, samarskite: 100;
geology: 100;
mineralization: 100;
mineralogy: 100;
structure: 100;
Las Tablas: samarskite, thorium, etc.: 40.
Lobato mine near Las Tablas: samarskite: 19, 69.
Miller mine S. of Canada la Jarita: monazite, samarskite: 42.
Petaca: 92.
Uranophane Occurrences—
Petaca Mining District:—
Claim 2½ mi. S.W. of Petaca: 69.

Rutherfordine Occurrences
See under individual county names and under Index III, Rutherfordine Occurrences—New Mexico.

Samarskite Occurrences
See under individual county names and under Index III, Samarskite Occurrences—New Mexico.

Sandoval County
Carnotite Occurrences—
Cochiti Mining District: 54.
Peralta Canyon: 40, 60, 69.
Lignites, Uranium-bearing, Occurrences—
General: 53.
Uranium Occurrences—
General: uranium-bearing lignites: 53.
Cochiti Mining District:
carnotite: 54.
Peralta Canyon: carnotite: 40, 60, 69.

San Juan County
Carnotite Occurrences—
Farmington: 99.
Navajo Indian Reservation: 161, 172.
Carrizo Mt.: 54.

NEW MEXICO (contd.)
Carrizo Mts.: 86, 87; E. flank: 69.
Claims subleased to V.C.A. by A.E.C.: 140.
Lukachukai Mts.: 185.
Uranium Occurrences—
Farmington: carnotite: 99.
Navajo Indian Reservation:
Carnotite: 140, 161, 172.
Carrizo Mt.: carnotite: 54.
Carrizo Mts.: carnotite: 86, 87; E. flank: carnotite: 69.
Claims subleased to V.C.A. by A.E.C.: 140.
Four Corners area: uranium deposits: 172.
Lukachukai Mts.: carnotite: 185; uranium claims: 186.
Navajos may reassign uranium mining rights: 178.
Uranium Prices—
Navajo Indian Reservation carnotites: percentage to Navajo owners: 140.
Uranium Processes—
Navajo Indian Reservation carnotites, treatment:
Durango, Colorado, plant when rehabilitated by V.C.A.: 140;
White Canyon District, Utah, pilot treatment plant: 140.
Shiprock: uranium ore sampling plant: 47, 185; plant to be built: 161; plant built by Navajo Uranium Co.: 47; plant flowsheet: 47; plant operated by A. S. & R.: 47; plant, problems of design and construction: 47; tonnage processed in plant: 47.
Uranium Production—
Shiprock: uranium ore-buying station for Navajo Indian Reservation uranium ores: 182; uranium ore sampling and purchasing depot: 186; uranium ore sampling plant: 47; uranium processing plant to be built: 186.
Uranium Purchases—
Shiprock: uranium ore-buying station: 53.

San Miguel County
Cyrtolite Occurrences—
Las Vegas, S.W. of: 69.
Monazite Occurrences—
Bull Creek, 15 mi. from Las Vegas: analysis: 68.
Bull Creek area, 15 mi. W. of Las Vegas: 69.
Elk Mt., E. of Willow Creek District: 69.
Pitchblende Occurrences—
Las Vegas, S.W. of: 69.
Samarskite Occurrences—
Elk Mt. area, W. of Las Vegas: 69.
Thorium Occurrences—
Bull Creek, 15 mi. from Las Vegas: monazite, analysis: 68.
Bull Creek area, 15 mi. W. of Las Vegas: monazite with uranium: 69.
Elk Mt., E. of Willow Creek District: monazite: 69.
Elk Mt., W. of Las Vegas: samarskite: 69.
Uranium Occurrences—
Bull Creek, 15 mi. from Las Vegas: monazite, analysis: 68.
Bull Creek area, 15 mi. W. of Las Vegas: monazite with uranium: 69.
Elk Mt. area W. of Las Vegas: samarskite: 69.
Las Vegas, S.W. of: cyrtolite, pitchblende: 69.

Santa Fe County
Monazite Occurrences—
Glorieta: 66, 69; really from Taos: 67.
Los Cerillos: 11
Tuer and Arroyo, area between: 69.
Thorium Occurrences—
Cerrillos Mining District, Galisteo monocline W. of Cerrillos Hills: allanite: 69.
Glorieta: monazite: 66, 69; monazite reported, really from Taos: 67.
Los Cerillos: monazite: 11.
Tuer and Arroyo, area between: monazite in black sand: 69.
Uranium Occurrences—
Glorieta: monazite reported, really from Taos: 67.

Schroeckingerite Occurrences
See under individual county names and under Index III, Schroeckingerite Occurrences—New Mexico.

Sierra County
Monazite Occurrences—
Pittsburg Mining District: 69.
Shandon: 11, 82; in black sands: 78.
Thorium Occurrences—
Pittsburg Mining District: monazite in black sand: 69.
Shandon: monazite: 11, 82; monazite in black sands: 78.

Socorro County
Autunite Occurrences—
San Lorenzo Mining District: (?) 54, 69.
Carnotite Occurrences—
Scholle: 54, 69, 93, 99.
Torbernite Occurrences—
San Lorenzo Gulch, Polvadera Hills, 6 mi. W. of San Acacia: 50.
San Lorenzo Mining District: (?) 54, 69.
Jerome Copper mine, N.E. side Limitar Mts.: 40.
Unnamed location: 49.
Uranium Occurrences—
San Lorenzo Gulch, Polvadera Hills, 6 mi. W. of San Acacia: torbernite: 50.
San Lorenzo Mining District: autunite, torbernite, uranophane: (?) 54, 69.
Jerome Copper mine, N.E. side Limitar Mts.: torbernite, uranophane: 40.
Jerome Copper mine: uranophane: 60.
Scholle: carnotite: 54, 69, 93, 99.
Unnamed location: torbernite: 49.
Uranophane Occurrences—
San Lorenzo Mining District: (?) 54, 69.
Jerome Copper mine, N.E. side Limitar Mts.: 40.
Jerome Copper mine: 60.

Taos County
Microlite Occurrences—
Harding mine (pegmatite), with beryl, 1 mi. E. of Dixon: 64, 98, 141.
Harding pegmatite: 65.
Microlite plant yields 95% recovery: 98.
Monazite Occurrences—
Taos, reported from Glorieta: 67.

Thorium Occurrences—
Harding mine area: unnamed thorium mineral with trace of uranium: 69.
Taos: monazite, reported from Glorieta: 67.
Uranium Occurrences—
Harding mine (pegmatite), 8 mi. E. of Dixon: microlite, beryl: 64, 98, 141.
Harding mine area: unnamed thorium mineral with trace of uranium: 69.
Harding pegmatite: microlite, beryl: 65; geology of deposit: 65.
Microlite recovery plant: 98.
Taos: monazite, reported from Glorieta: 67.

Thorium Occurrences
See under individual county names and under Index III, Thorium Occurrences—New Mexico.
Bibliography: 4, 9.

Thorium Processes
See under individual county names and under Index III, Thorium Processes—New Mexico.

Thorium Production
See under individual county names and under Index III, Thorium Production—New Mexico.

Torbernite Occurrences
See under individual county names and under Index III, Torbernite Occurrences—New Mexico.

Tyuyamunite Occurrences
See under individual county names and under Index III, Tyuyamunite Occurrences—New Mexico.

Uraninite Occurrences
See under individual county names and under Index III, Uraninite Occurrences—New Mexico.

Uranium Development
See under individual county names and under Index III, Uranium Development—New Mexico.

Uranium Exploration
See under individual county names and under Index III, Uranium Exploration—New Mexico.
Drilling Programs:—
U.S.A.E.C. (by private contractors), methods and results: 18.
U.S.B.M., methods and results: 18.
U.S.G.S., methods and results: 18.

Uranium Occurrences
See under individual county names and under Index III, Uranium Occurrences—New Mexico.
Bibliography: 4, 9, 10.

Uranium Prices
See under individual county names and under Index III, Uranium Prices—New Mexico.

Uranium Processes
See under individual county names and under Index III, Uranium Processes—New Mexico.

Uranium Production
See under individual county names and under Index III, Uranium Production—New Mexico.

Uranium Prospecting
See under individual county names and under Index III, Uranium Prospecting—New Mexico.

Uranium Purchases
See under individual county names and under Index III, Uranium Purchases—New Mexico.

Uranophane Occurrences
See under individual county names and under Index III, Uranophane Occurrences—New Mexico.

Valencia County
Carnotite Occurrences—
Grants area, in Morrison fm.: 89.
Grants area, in Todilto limestone: 89.
Santa Fe Railway land: 165, 175.
Copper-Uranium Deposits—
Copper Hill: 107.
Schroeckingerite Occurrences—
Grants area, in Morrison fm.: 89.
Tyuyamunite Occurrences—
Grants area, in Todilto limestone: 89.
Santa Fe Railway land, in Todilto limestone: 173.
Uranium Development—
Grants area: 88.
Laguna Indian Reservation:
Anaconda to explore and develop: 181;
Indians to get uranium royalties: 181.
Uranium Exploration—
Grants area: test-pitting: 89; wagon-drilling: 89.
Uranium Occurrences—
Copper Hill: uranium oxide with copper: 107.
Grants area: carnotite in Brushy Basin sandstone: 53; carnotite in Recapture sandstone: 53; carnotite in Todilto limestone: 53; carnotite and schroeckingerite in Morrison fm.: 89; carnotite, tyuyamunite, and uranophane in Todilto limestone: 89; pitchblende: 89; uranium deposits: 88.
Operation Haystack, W. of Grants: uranium deposit: 170.
Santa Fe Railway land: carnotite: 165, 175;
low-grade uranium ore: 172;
tyuyamunite in Todilto limestone: 173;
uranium deposits: 174;
uranium production by Haystack Mountain Development Co., a subsidiary: 177.
Laguna Indian Reservation:
Anaconda to explore and develop: 181;
uranium deposits: 170; 180.
Laguna Indian Reservation, 50 mi. W. of Albuquerque: uranium deposits: 177.
Uranium Processes—
Bluewater area: Anaconda to build mill: 177, 181.
Grants area: plant to be built by Anaconda for operation in 1953: 180.
Uranium Production—
Bluewater area: Anaconda to build mill: 177, 181.
Santa Fe Railway land: uranium produced by Haystack Mountain Development Co.: 177.
Uranophane Occurrences—
Grants area, in Todilto limestone: 89.

UNITED STATES
General
Uranium Bonus—
U.S.A.E.C. Bonus: 2, 187; Colorado Plateau: 163.
Uranium prices—
Minimum prices guaranteed: 2, 187.
Uranium Production—
U.S.A.E.C. Bonus as incentive: Colorado Plateau: 163.
Uranium Prospecting—
Suggestions for prospecting work: 63.

INDEX III

SUBJECT INDEX FOR ARIZONA, NEVADA, AND NEW MEXICO

(Numbers refer to References Listed in Bibliography)

A

ALLANITE MINERALOGY
General
Chemical composition: 23, 24.
Physical properties: 23, 24.

ALLANITE OCCURRENCES
Arizona
See Thorium Occurrences—Arizona: 2, 6, 23, 24.
Nevada
See Thorium Occurrences—Nevada: 79.
New Mexico
See Thorium Occurrences—New Mexico: 69.

ANDERSONITE MINERALOGY
General
Analyses: Arizona specimen: 3.
Physical Properties: 3.

ANDERSONITE OCCURRENCES
Arizona
Yavapai County—
Hillside mine N. of Bagdad: 3, 103, 138, 151.

ASPHALTITES, URANIUM-BEARING, OCCURRENCES
Nevada
Eureka County—
Unnamed location in Pinon Range, 15 mi. S. of Palisade: 26.

AUTUNITE OCCURRENCES
Nevada
Nye County—
Round Mt.:
Tonopah, some 6-8% uranium ore: 157.
New Mexico
Grant County—
Big Burro Mt.:
Ra-Tor-Plac Co.'s 3 claims, 10 mi. S. of Phelps Dodge camp at Tyrone: 56.
Eureka Mining District (?): 69.
White Oaks (should read: White Signal) Mining District, 9 mi. S. of Tyrone: 33.
White Signal Mining District: 54, 69, 102.
Acme claim: 57.
Burro Mts., 4 mi. E. of, in diabase dikes: 55.
Foster claim: 57.
Grissom claim: 57.
Merry Widow claim: 57.
Shamrock claim: 57.
Tullock mine: 57.
Hidalgo County-
Sylvanite Mining District: 69.
Socorro County—
San Lorenzo Mining District: (?) 54, 69.

B

BASTNASITE OCCURRENCES
Nevada
Clark County—
Clark Mt.: 162.
New Mexico
Lincoln County—
Gallinas Mining District: 183.
Gallinas Mts.: 179.
All American prospect near head of Red Cloud Canyon: 76.
Eagle Nest claim No. 2: 8.
Eagle Nest prospect ¾ mi. N. of Red Cloud mine on SW-trending spur of Rough Mt.: 76.
Red Cloud prospect in Red Cloud Canyon: 76.

BAYLEYITE MINERALOGY
General
Analyses: Arizona specimen: 3.
Physical Properties: 3.

BAYLEYITE OCCURRENCES
Arizona
Yavapai County—
Hillside mine N. of Bagdad: 3, 103, 138, 151.

BIBLIOGRAPHIES
Arizona
Carnotite Occurrences: 61, 96.
Monazite Occurrences: 96.
Thorium Occurrences: 9, 96.
Uranium Occurrences: 9, 10, 61, 96.
Carnotite Occurrences
Arizona: 61, 96.
Monazite Occurrences
Arizona: 96.
Nevada
Thorium Occurrences: 9.
Uranium Occurrences: 9, 10, 26.
New Mexico
Thorium Occurrences: 4, 9.
Uranium Occurrences: 4, 9, 10.
Thorium Occurrences
Arizona: 9, 96.
Nevada: 9.
New Mexico: 4, 9.
Uranium Occurrences
Arizona: 9, 10, 61, 96.

Nevada: 9, 10, 26.
New Mexico: 4, 9, 10.

C

CARNOTITE MINERALOGY

General
Chemical composition: 1, 23, 24; tests: 1.
Physical properties: 1, 23, 24.

Nevada
Specimens compared: 37.

CARNOTITE OCCURRENCES

Arizona
General: 7; (in) Morrison fm.: 22; (in) Petrified wood: 148; (in) Shinarump conglomerate: 22.
Northeast part: 14.
Apache County—
Navajo Indian Reservation:
General: 1, 16, 41, 78, 82, 108, 109, 147, 150, 161, 166.
Carrizo Mts.: 7, 86, 87. West of: 2, 23, 24.
Claims subleased to V.C.A. by A.E.C.: 140.
Four Corners area: 17.
Lukachukai Basin S. of Red Rock: 166.
Lukachukai Mts.: 63, 167.
Mesa Four-and-a-Half: 51.
Mesa V, 10 mi. W. of Red Rock, in Salt Wash, Morrison fm.: 51.
Bibliography: 61, 96.
Cochise County—
Tombstone Mining District: 1, 7.
Coconino County—
Hack's Canyon near Fredonia: 17.
Vermillion Cliffs, in petrified wood: 146; 3% uranium: 142.
Gila County—
Mercer-King Consolidated Mines, Ltd., near Radium: 125.
Vanadinite Group of claims, 3 mi. N. of Globe: 41.
Maricopa County—
Aguila: 120.
Vulture Mts., S. of Aguila: 2, 23, 24, 34.
Ray's Camp area near Aguila: 36, 38.
Treloar's claims near Aguila: 36, 38.
Navajo County—
Kayenta area: 7.
Monument Valley: 2, 7, 23, 24.

Bibliographies
Arizona: 61, 96.

Colorado Plateau
General:
Morrison fm.: 22.
Shinarump conglomerate: 22.

Morrison Formation
General:
Arizona: 22.
Colorado Plateau: 22.
New Mexico: 22.

Nevada
General: 117.
Clark County—
Sloan Mining District:
Sloan: 26, 34.
2 mi. S. of: 59, 126.
Sutor Mining District:
Sutor, 2 mi. W. of: 126.
Sutor area, several deposits: 37, 59.
Yellow Pine Mining District:
Goodsprings: 126.
2 mi. N. of: 59.
Humboldt County—
Virgin Valley, in opal: 85.
Lincoln County—
Atlanta Mining District: 59.
Atlanta mine: 37, 39, 82, 126.
Pioche: 34.

New Mexico
General:
Morrison fm.: 22.
Unnamed location, N.W. part of state: 93.
McKinley County—
Grants area:
Santa Fe Railway land: 176.
Sandoval County—
Cochiti Mining District: 54.
Peralta Canyon: 40, 60, 69.
San Juan County—
Farmington: 99.
Navajo Indian Reservation: 161, 172.
Carrizo Mt.: 54.
Carrizo Mts.: 86, 87; E. flank: 69.
Claims subleased to V.C.A. by A.E.C.: 140.
Lukachukai Mts.: 185.
Socorro County—
Scholle: 54, 69, 93, 99.
Valencia County—
Grants Area:
(in) Brushy Basin sandstone: 53.
(in) Morrison fm.: 89.
(in) Recapture sandstone: 53.
(in) Todilto limestone: 53, 89.
Santa Fe Railway land: 165, 175.

Ore Bodies
General:
Geology: 87.
Origin: 87.
Prospecting: 87.

Sandstone, in
Arizona:
General: 46.
New Mexico:
General: 46.

Shinarump Conglomerate
General:
Arizona: 22.
Colorado Plateau: 22.

CHANNEL DEPOSITS, URANIUM-BEARING

Channel Deposits, Uranium-bearing: See Morrison Formation: 22.

CHEVKINITE MINERALOGY

General
Analyses: Arizona specimen: 44.
Chemical composition: 24.
Physical properties: 24.
X-ray examination: Arizona specimen: 44.

CHEVKINITE OCCURRENCES

Arizona
Mohave County—
Aquarius Mts.: 2, 24, 44.

CLAYS, URANIUM-BEARING, OCCURRENCES

Arizona
Mohave County—
Aquarius Mts.: euxenite: 122.

Nevada
Lincoln County—
Patterson Mining District:
Cave Valley cave: 80.

COPPER-URANIUM DEPOSITS

Arizona
Coconino County—
Hack's Canyon in copper mine: 15, 16.
Navajo Bridge, E. & N. of: 21.
Mohave County—
Rainbow claims W. of Pipe Springs National Monument: 21.

New Mexico
Valencia County—
Copper Hill: 107.

CYRTOLITE OCCURRENCES

New Mexico
San Miguel County—
Las Vegas, S.W. of: 69.

D–E

EUXENITE MINERALOGY

General
Chemical composition: 23, 24.
Physical properties: 23, 24.

EUXENITE OCCURRENCES

Arizona
Mohave County—
Aquarius Mts., in clay: 122.
Big Sandy River, E. of, S. of Burro Creek: 2, 23, 24.
Kingman Feldspar mine, Cerbat Range: 2, 23, 24.

F

FERGUSONITE MINERALOGY

General
Chemical composition: 23, 24.
Physical properties: 23, 24.

FERGUSONITE OCCURRENCES

Arizona
Mohave County—
Oatman Route, Kingman: 17.
Yavapai County—
Yarnell Hill area: 23, 24.

New Mexico
Rio Arriba County—
Petaca Mining District:
Fridlund dike, 2½ mi. S. of Petaca: 69.

FLUORESCENCE

General
Definition: 32.
Methods of detection: 32.
Minerals: 32.

FLUORESCENT MINERALS, URANIUM-BEARING, OCCURRENCES

New Mexico
General:
Mineral headings: autunite, johannite, meta-torbernite, schroeckingerite, torbernite: 32.

FLUORITE, URANIUM-BEARING, OCCURRENCES

New Mexico
General: 95.

G

GADOLINITE MINERALOGY

General
Chemical composition: 23, 24.
Physical properties: 23, 24.

GADOLINITE OCCURRENCES

Arizona
See Thorium Occurrences—Arizona: 2, 23, 24, 30, 108, 109.

GUMMITE OCCURRENCES

New Mexico
McKinley County—
Grants area:
Santa Fe Railway land: 176.
Rio Arriba County—
Petaca Mining District: 54.
Beryl Prospect N. of Cribbensville & S. of Canada la Jarita: 42.
Claim 2½ mi. S.W. of Petaca: 69.

H–K

KASOLITE OCCURRENCES

Arizona
Pima County—
Iris claims: 103.
Lena claims: 103.
St. Joe claims: 103.

KITHILITE OCCURRENCES

New Mexico
Grant County—
White Signal Mining District:
Camp Kithil near Silver City: 111.
Tyrone: 58.

L

LATERITES, URANIUM-BEARING, OCCURRENCES

Arizona
Navajo County—
Oljeto N. of Kayenta: 72.

LIGNITES, URANIUM-BEARING, OCCURRENCES

General
Nevada: 27; New Mexico: 53, 62.

Nevada
General: 27.

New Mexico
General: 62.
Rio Arriba County—General: 53.
Sandoval County—General: 53.

LIMESTONES, URANIUM-BEARING, OCCURRENCES

General
New Mexico: 27.

New Mexico
General: 27.
McKinley County—
Zuni Uplift: 20.

M

META-TORBERNITE OCCURRENCES

Arizona
Cochise County—
"Howard" claim: 103.
Pima County—
Papago Chief mine: 103.

MICROLITE OCCURRENCES

Arizona
Maricopa County—
Morristown, E. of: 17.

New Mexico
Mora County—
Pidlite pegmatite: 70.
Taos County—
Harding mine (pegmatite) with beryl, 8 mi. E. of Dixon: 64, 65, 98, 141.

MONAZITE MINERALOGY

General
Chemical composition: 23, 24.
New Mexico: pilot analysis made of specimen: 67; specimens analyzed: 66.
Physical properties: 23, 24.

MONAZITE OCCURRENCES

Arizona
Bibliography: 96.
Mohave County—
Aquarius Mts.: 2, 24, 44.
Chemehuevis District, Mohave Mts., 20 mi. S.E. of Topock: 2, 23, 24, 31.
Yavapai County—
Black Canyon Creek: 11.

Bibliographies
Arizona: 96.

Nevada
Ormsby County—
Carson City: 11, 59, 82; in black sands: 78.

New Mexico
General: 117.
Dona Ana County—
Organ Mining District: 69.
Middle Rio Grande Valley: 74.
Valencia County—
Bosque, 0.6% or less in Rio Grande River sands: 75.
Rio Arriba County—
Chama River: 40, 69.
Petaca Mining District:
Beryl Prospect N. of Cribbensville & S. of Canada la Jarita: 42.
Cribbenville mine, Petaca: 66, 69.
Fridlund claim, 2½ mi. S.W. of Petaca: 35.
Fridlund mine S. of Canada la Jarita: 42.
Globe mine: 100.
Globe pegmatite: 100.
Las Tablas: 19.
Miller mine S. of Canada la Jarita: 42.
San Miguel County—
Bull Creek, 15 mi. from Las Vegas: analysis: 68.
Bull Creek area, 15 mi. W. of Las Vegas: 69.
Elk Mt., E. of Willow Creek District: 69.
Santa Fe County—
Glorieta: 66, 69; really from Taos: 67.
Los Cerillos: 11.
Tuer and Arroyo, area between: 69.
Sierra County—
Pittsburg Mining District: 69.
Shandon, 11, 82; in black sands: 78.
Taos County—
Taos, reported from Glorieta: 67.

MORRISON FORMATION

Carnotite Occurrences
General:
Arizona: 22.
Colorado Plateau: channel deposits: 22; genesis: 22; geology: 22; ore deposits: 22; uranium production: 22.
New Mexico: 22.

N–O

OPAL, URANIUM-BEARING, OCCURRENCES

Nevada
Humboldt County—
Virgin Valley: carnotite: 85.

P

PETRIFIED WOOD, URANIUM-BEARING, OCCURRENCES

General 1.

Arizona
General: carnotite: 148.
Coconino County—
Lee's Ferry: 21.
Marble Canyon: 21.
Vermillion Cliffs: 16, 144.
carnotite: 142, 146.
Navajo County—
Holbrook, S. of: 144.

PITCHBLENDE MINERALOGY

General
Physical properties:
Arizona specimen: 101.
Radiometric analyses:
Arizona specimen: 101.

PITCHBLENDE OCCURRENCES

Arizona
Mohave County—
Jim Kane mine N.W. of Kingman: 103.
Pima Country—
Ajo Mining District:
J. M. Pope's seven claims, samples analyzed: 110.
Lena claims: 103.
Pinal County—
Kate No. 3 claim: 103.
Santa Cruz County—
Annie Laurie claims: 103.
Annie Laurie prospect near Ruby: 101.
Wrightson Mining District:
Happy Jack mine: 7, 103.
Yavapai County—
Hillside mine N. of Bagdad: 103.
W. H. Slaughter's mine near Columbia: 105.

Nevada
Humboldt County—
Rocky Canyon, vein being developed: 188.
Lyon County—
Southern part: 155.

New Mexico
Grant County—
Black Hawk Mining District: 69.
White Signal Mining District:
Black Hawk camp at Bullard's Peak, 12 mi. N. W. of Tyrone: 57.
Merry Widow mine at Silver City: 127.
Tyrone: 58.
McKinley County—
Grants area:
Santa Fe Railway land: 176.
Zuni Uplift area 5 mi. N. of Prewitt: 63.
Rio Arriba County—
Petaca Mining District:
Claim 2½ mi. S.W. of Petaca: 69.
San Miguel County—
Las Vegas, S.W. of: 69.

PYROMORPHITE, URANIUM-BEARING, OCCURRENCES

Arizona
Graham County—
Golondrina claims: 103.
Santa Cruz County—
"Spelbrink" claim: 103.

Q

QUARTZITE, RADIOACTIVE

Quartzite, Radioactive: See Radioactive Quartzite: 17.

QUARTZITE, URANIUM-BEARING, OCCURRENCES

Arizona
Gila County—
Red Bluff Prospect:
Dripping Springs quartzite: 43.

R

RADIOACTIVE AREAS

Arizona
Pinal County—
Magma mine, Superior: sulphide minerals: 45.

Nevada
Esmeralda County—
Mohawk property: radioactive mineral: 171.
Lyon County—
Rink claim, Cambridge Mining Co., near Yerington: radioactive deposits: 128.

New Mexico
Grant County—
Hanover: lead-zinc ore: 45.

RADIOACTIVE MINERALS, THORIUM-BEARING, OCCURRENCES

New Mexico
General:
Minerals named: 32.

RADIOACTIVE MINERALS, URANIUM-BEARING, OCCURRENCES

New Mexico
General:
Minerals named: 32.

RADIOACTIVE QUARTZITE

Arizona
Gila County—
Dripping Springs quartzite: 43.
Globe, 35 mi. N. of: 17.

RADIOACTIVE ROCKS

Arizona
Gila County—
Dripping Springs quartzite: 43.
Globe, 35 mi. N. of: radioactive quartzite found by the Carl Larsons: 17.

RADIOACTIVE SPRINGS

Arizona
Yavapai County—
Castle Hot Springs in foothills of Bradshaw Mts.: radioactive but no radium content: 5.
Yuma County—
Radium Hot Springs near S.E. margin of Muggins Mts.: radium emanation in water: 97.

RADIOACTIVITY

General
Definition: 32.
Methods of detection: 32;
electroscope: 2;
Geiger-Muller Counter, description: 2; use: 2;
photographic: 2.
Minerals: 32.

RADIUM OCCURRENCES

General: 113.
New Mexico
See Uranium Occurrences—New Mexico: 92.

RUTHERFORDINE OCCURRENCES

New Mexico
McKinley County—
Grants area:
Santa Fe Railway land: 176.

S

SALT WASH, MORRISON FORMATION

Uranium Occurrences
Arizona:
Carrizo Mts.: uranium & vanadium oxides: 52.
Lukachukai Mts.: carnotite: 51.

SAMARSKITE MINERALOGY

General
Chemical composition: 23, 24.
New Mexico: genesis of specimen: 35, radiograph analysis of specimen: 35.
Physical properties: 23, 24.

SAMARSKITE OCCURRENCES

Arizona
Mohave County—
Aquarius Mts.: 2, 23, 24, 44.
Kingman, N.E. of: 17.
Yavapai County—
Black Hills near Jerome: 2, 23, 24.

New Mexico
Rio Arriba County—
Petaca Mining District:
54; in pegmatite: 70.
Beryl Prospect N. of Cribbensville & S. of Canada la Jarita: 42.
Fridlund claim, 2½ mi. S.W. of Petaca: 35.
Fridlund dike, 2½ mi. S. of Petaca: 69.
Fridlund mine S. of Canada la Jarita: 42.
Globe mine: 100.
Globe pegmatite: 100.
Las Tablas: 40.
Lobato mine near Las Tablas: 19, 69.
Miller mine S. of Canada la Jarita: 42.
San Miguel County—
Elk Mt. area, W. of Las Vegas: 69.

SCHROECKINGERITE MINERALOGY

General
Analyses: Arizona specimen: 3.
Physical properties: 3.

SCHROECKINGERITE OCCURRENCES

Arizona
Yavapai County—
Hillside mine N. of Bagdad: 3, 138.

New Mexico
Valencia County—
Grants area, in Morrison fm.: 89.

SHINARUMP CONGLOMERATE

Carnotite Occurrences
General:
Arizona: 22.

SWARTZITE MINERALOGY

General
Analyses: Arizona specimen: 3.
Physical properties: 3.

SWARTZITE OCCURRENCES

Arizona
Yavapai County—
Hillside mine N. of Bagdad: 3, 103, 138, 151

T

THORIUM MINERALS

Mineralogy
General: lists of equivalent names: 58.

THORIUM OCCURRENCES

Arizona
General: 12, 25.
Bibliography: 9, 96.
Cochise County—
Tombstone Mining District: allanite: 2, 23, 24; allanite in granodiorite: 6.
Mohave County—
Aquarius Mts.: allanite, chevkinite, gadolinite, monazite, samarskite: 2, 24, 44; allanite, gadolinite in pegmatites, samarskite: 23.
Big Sandy River, E. of, S. of Burro Creek: euxenite: 2, 23, 24.
Chemehuevis Mining District, Mohave Mts., 20 mi. S.E. of Topock: monazite: 2, 23, 24; monazite in stream gravels: 31.
Hackberry, 20 mi. S. of: gadolinite in pegmatite: 108, 109.
Kingman: gadolinite: 30.
Kingman, N.E. of: samarskite: 17.
Kingman Feldspar mine, Cerbat Range: allanite, euxenite: 2; allanite in pegmatite, euxenite, gadolinite: 23; euxenite, gadolinite: 24.
North part: gadolinite in sand dunes: 24.
Oatman Route, Kingman: fergusonite: 17.
Yavapai County—
Black Canyon Creek: monazite: 11.
Black Hills near Jerome: samarskite: 2, 23, 24.
Eureka Mining District on 7-U-7 Ranch near Bagdad: allanite, torbernite: 2; allanite: 23, 24.
Yarnell Hill area: fergusonite: 23, 24.

Bibliographies
Arizona: 9, 96.
Nevada: 9.
New Mexico: 4, 9.

Nevada
General: 12, 25.
Bibliography: 9.
Clark County—
Clark Mt.: bastnasite: 162.
Elko County—
Contact Mining District: allanite: 79.
Ormsby County—
Carson City: monazite: 11, 82; monazite in black sands: 59, 78.

New Mexico
General: 12, 25; monazite: 117.
Bibliography: 4, 9.
Dona Ana County—
Organ Mining District: monazite: 69.
Lincoln County—
Gallinas Mining District: bastnasite: 183.
Gallinas Mts.: bastnasite: 179.
Eagle Nest claim No. 2: bastnasite: 8.
Red Cloud Canyon: bastnasite: 76.
McKinley County—
Grants area:
Santa Fe Railway land: gummite, rutherfordine in Todilto limestone: 176.
Middle Rio Grande Valley:—
monazite: 74.
Valencia County—
Bosque: monazite in Rio Grande River sands: 75.
Rio Arriba County—
Chama River: monazite in sand: (?) 40, 69.
Petaca Mining District: gummite, samarskite, uraninite, uranophane: 54; samarskite in pegmatite: 70.
Beryl Prospect N. of Cribbensville & S. of Canada la Jarita: gummite, monazite, samarskite, uraninite: 42.
Claim 2½ mi. S.W. of Petaca: gummite, pitchblende, uranophane: 69.
Cribbenville mine, Petaca: monazite with uranium: 66, 69.
Fridlund claim, 2½ mi. S.W. of Petaca: monazite, samarskite, uraninite: 35.
Fridlund dike, 2½ mi. S. of Petaca: fergusonite, samarskite, uraninite: 69.
Fridlund mine S. of Canada la Jarita: monazite, samarskite: 42.
Globe mine: monazite, samarskite: 100.
Globe pegmatite: monazite, samarskite: 100.
Las Tablas: monazite: 19; samarskite, thorium, etc.: 40.
Lobato mine near Las Tablas: samarskite: 19, 69.
Miller mine S. of Canada la Jarita: monazite, samarskite: 42.
San Miguel County—
Bull Creek, 15 mi. from Las Vegas: monazite, analysis: 68.
Bull Creek area, 15 mi. W. of Las Vegas: monazite with uranium: 69.
Elk Mt., E. of Willow Creek District: monazite: 69.
Elk Mt., W. of Las Vegas: samarskite: 69.
Santa Fe County—
Cerrillos Mining District, Galisteo monocline W. of Cerrillos Hills: allanite: 69.
Glorieta: monazite: 66, 69; monazite reported, really from Taos: 67.
Los Cerillos: monazite: 11.
Tuer and Arroyo, area between: monazite in black sand: 69.
Sierra County—
Pittsburg Mining District: monazite in black sand: 69.
Shandon: monazite: 11, 82; monazite in black sands: 78.
Taos County—
Harding mine area: unnamed thorium mineral with trace of uranium: 69.
Taos: monazite, reported from Glorieta: 67.

THORIUM PROCESSES
New Mexico
Lincoln County—
Gallinas Mts.: mill for processing bastnasite: 179.

THORIUM PRODUCTION
New Mexico
Lincoln County—
Gallinas Mts.: bastnasite ore processed: 179.

TORBERNITE MINERALOGY
General
Chemical composition: 23, 24.
Physical properties: 23, 24.

TORBERNITE OCCURRENCES
Arizona
General:
Northwest part: 14.
Gila County—
Castle Dome mine, Miami Mining District: 2, 24.
Yavapai County—
Eureka Mining District on 7-U-7 Ranch near Bagdad: 2, 23, 24.
Nevada
Nye County—
Round Mt.:
Tonopah: 133, 134.
Pershing County—
Antelope Mining District:
Majuba Hill: 84.
New Mexico
General: 118.
Grant County—
Big Burro Mt.:
Ra-Tor-Plac Co.'s 3 claims, 10 mi. S. of Phelps Dodge camp at Tyrone: 56.
White Oaks (should read: White Signal) Mining District, 9 mi. S. of Tyrone: 33.
White Signal Mining District: 54, 69, 102.
Acme claim: 57.
Burro Mts., 4 mi. E. of, in diabase dike: 55.
Camp Kithil: 112.
Foster claim: 57.
Grissom claim: 57.
Merry Widow claim: 28, 57.
Merry Widow mine at Silver City: 127.
Otto Forester's radium mine, 1 mi. S. of White Signal post office: 19.
Shamrock claim: 57.
Signal City: 93.
Silver City: 99, 115.
Tullock mine: 57.
Tyrone: 58.
Socorro County—
San Lorenzo Gulch, Polvadera Hills, 6 mi. W. of San Acacia: 50.
San Lorenzo Mining District: (?) 54, 69.
Jerome Copper mine, N.E. side Limitar Mts.: 40.
Unnamed location: 49.

TYUYAMUNITE MINERALOGY
General
Chemical compositions: 23, 24.
Physical properties: 23, 24.

TYUYAMUNITE OCCURRENCES

Arizona
Cochise County—
Bisbee: 2, 23, 24, 34.

New Mexico
McKinley County—
Grants area: Santa Fe Railway land: 176.
Valencia County—
Grants area, in Todilto limestone: 89.
Santa Fe Railway land in Todilto limestone: 173.

U

URANINITE OCCURRENCES

Arizona
Colfax County—
President mine near Elizabethtown: 104.
Pima County—
Black Dike claims: 103.
Santa Cruz County—
Harshaw Mining District: 81.
Wrightson Mining District:
Happy Jack mine: 81, 82.

New Mexico
Rio Arriba County—
Petaca Mining District: 54.
Beryl Prospect N. of Cribbensville & S. of Canada la Jarita: 42.
Fridlund claim, 2½ mi. S.W. of Petaca: 35.
Fridlund dike, 2½ mi. S. of Petaca: 69.

URANIUM BONUSES

Colorado Plateau
U.S.A.E.C. Bonus: 163, 187.

United States
U.S.A.E.C. Bonus: 2, 187;
Colorado Plateau: 163.

URANIUM DEVELOPMENT

Arizona
Apache County—
Navajo Indian Reservation:
Lukachukai Mts.: mining recommendations: 169; ore reserves developed: 169.
Gila County—
Mercer-King Consolidated Mines, Ltd., near Radium: concentration plant may be built: 125; mine to be developed: 125.

Colorado Plateau
General: 73.

Nevada
Nye County—
Round Mt.:
Heneberg property (or Rainbow claims): uranium deposits: 137, 143; new development work: 158.
Tonopah: commercial uranium: 133.

New Mexico
Grant County—
White Signal Mining District:
Merry Widow mine at Silver City: shaft deepened: 127.
Tyrone: torbernite being mined: 58.
McKinley County—
Grants area: 88.
Santa Fe Railway land: 73; development work: 176.
Valencia County—
Grants area: 88.
Laguna Indian Reservation: Anaconda to explore and develop: 181; Indians to get uranium royalties: 181.

URANIUM EXPLORATION

Arizona
Apache County—
Navajo Indian Reservation:
drilling program for 1951: 144.
Drilling Programs:
General: 18.

Colorado Plateau
Drilling Programs—
U.S.A.E.C. (by private contractors), methods and results: 18.
U.S.B.M., methods and results: 18.
U.S.G.S., methods and results: 18.

Navajo Indian Reservation
General:
Navajo finders can claim ore: 77.
U.S.A.E.C. Training Program for Indians: 77.

Nevada
General: tests by Uranium Vanadium Exploration Co.: 139.

New Mexico
Drilling Programs—
General: 18.
Valencia County—
Grants area: test-pitting: 89; wagon-drilling: 89.

URANIUM MINERALS

Mineralogy
General: lists of equivalent names: 58.
Chemical composition: 2.
Physical properties: color: 2; crystal form; 2; hardness: 2; lustre: 2; specific gravity: 2.

URANIUM MINING

Navajo Indian Reservation
New regulations for non-Indians: 186.

URANIUM OCCURRENCES

Arizona
General: 12, 13, 25.
Carnotite: 7
Carnotite in petrified wood: 148.
Carnotite in sandstone: 46; in sandstone deposits: 62.
Clare Pearson property: ore samples carry up to 10% uranium: 144.
Copper-uranium deposits: 62.
First commercial deposit in state: 148.
Hydrothermal vein deposits: 62.
Northeast part: carnotite: 14.
Northwest part: inaccessible deposit with 1.5% uranium in ore; not to be developed: 136; torbernite: 14.
Possible occurrences: 71.

URANIUM OCCURRENCES (contd.)
Arizona (contd.)
Apache County—
Navajo Indian Reservation:
Carnotite: 1, 16, 41, 78, 82, 108, 109, 140, 147, 150, 161, 166.
Claims subleased to V.C. A. by A.E.C.: 140.
Uranium Deposits: 178.
Uranium in limestone: 164.
Uranium production: 184.
V.C.A. operations: 200 t. uranium ore daily: 149.
Carrizo, 3 mi. W. of: uranium: 144; 12 mi. W. of: uranium: 144.
Carrizo Mts.: carnotite: 7, 86, 87.
West of: carnotite: 2, 24; carnotite in Morrison (McElmo) sandstone: 23.
Cove Mesa: uranium & vanadium oxides in Salt Wash: 52.
Cove Mesa, 14 mi. W. of Red Rock: uranium: 144.
Red Rock, 5 mi. N. of: uranium: 144.
Red Rock District: uranium & vanadium oxides in Salt Wash: 52.
Kinusta (Tree) Mesa: uranium & vanadium oxides in Salt Wash: 52.
Four Corners area: carnotite: 17.
Lukachukai Basin: uranium deposits: 150; South of Red Rock: carnotite: 166.
Lukachukai Mts.: carnotite: 63, 167; new uranium discoveries: 77; uranium: 169.
Fred Sitton property: uranium deposit: 153.
Mesa Four-and-a-Half: carnotite: 51.
Mesa V, 10 mi. W. of Red Rock: carnotite and vanadium minerals in Salt Wash, Morrison fm.: 51.
Unnamed location 23 mi. S. of Mexican Hat, Utah: uranium: 144.
Bibliography: 9, 10, 61, 96.
Cochise County—
Bisbee: tyuyamunite: 2, 23, 24, 34.
"Howard" claim: metatorbernite in quartz-wolframite veins: 103.
Tombstone Mining District: carnotite: 1, 7.
Valley View claim: uranium oxide: 103.
Coconino County—
Flagstaff, N. of: uranium oxide content, 1.5%: 116.
Hack's Canyon in copper mine: copper-uranium ores: 15; copper-uranium ores, metallurgy under study; 16.
Hack's Canyon near Fredonia: carnotite to be developed: 17; carnotite to be treated at Marysvale, Utah, plant: 17.
Lee's Ferry: uranium in petrified wood: 21.
Marble Canyon: uranium in petrified wood: 21.
Navajo Bridge, E. & N. of: copper-uranium deposits: 21.
Vermillion Cliffs: carnotite in petrified wood: 146; 3% uranium: 142; uranium in petrified wood: 16, 144.
Gila County—
Castle Dome mine, Miami Mining District: torbernite: 2, 24.
Mercer-King Consolidated Mines, Ltd., near Radium: carnotite: 125.
Red Bluff claims: secondary uranium minerals: 103.
Red Bluff Prospect in S. end of Sierra Ancha 12 mi. N.E. of Roosevelt Dam: uranium in Dripping Springs quartzite: 43.
Parker Creek Canyon:
uranium in Dripping Springs quartzite: 43.
Warm Creek Canyon:
uranium in Dripping Springs quartzite: 43.
Vanadinite Group of claims, 3 mi. N. of Globe: carnotite: 41.
Graham County—
Golondrina claims: uranium in pyromorphite: 103.
Maricopa County—
Aguila: carnotite: 120.
Morristown, E. of: microlite, produced by Anderson Bros.: 17.
Prince of Arizona mine, 8 mi. N. of Beardsley station & 31 mi. N.W. of Phoenix: uranium oxides: 94.
Maricopa County—
Vulture Mts. S. of Aguila: carnotite: 2, 24, 34; carnotite in tuff: 23.
Ray's camp area near Aguila: carnotite: 38: carnotite in tuffs: 36.
Treloar's claims near Aguila: carnotite: 36, 38.
Mohave County—
Aquarius Mts.: allanite chevkinite, gadolinite, monazite, samarskite: 2; euxenite in clay: 122; samarskite: 23, 24.
Big Ledge claims S.E. of Kingman, Cottonwood Mts.: uranium in red jasper: 103.
Big Sandy River, E. of, S. of Burro Creek: euxenite: 2.
Jim Kane mine N.W. of Kingman: pitchblende: 103.
Kingman, N.E. of: samarskite, produced in commercial quantities: 17.
Kingman Feldspar mine, Cerbat Range: allanite, euxenite: 2.
Oatman Route, Kingman: fergusonite, mined & concentrated by L. L. Edgerton: 17.
Rainbow claims W. of Pipe Springs National Monument: copper-uranium deposits: 21.
Red Hills claims: secondary uranium minerals: 103.
Navajo County—
Kayenta area: carnotite: 7.
Holbrook, S. of: 31
uranium claims: 144; uranium content of ore, 4–5%: 144; uranium in petrified wood in Chinle fm.: 144.
Monument Valley: carnotite: 2, 7, 24; carnotite in Shinarump sandstone: 23.
Navajo Indian Reservation: uranium production: 184.
Oljeto N. of Kayenta: uranium in laterite of McElmo age: 72.
Pima County—
Ajo Mining District:
J. M. Pope's seven claims: pitchblende, samples analyzed: 110.
Black Dike claims: uraninite: 103.
Glen claims: uranium in granite: 103.
Iris claims: kasolite: 103.
Lena claims: kasolite, pitchblende: 103.
Natalia claims: uranium deposit: 103.
Papago Chief mine, 65 mi. from Tucson:

metatorbernite, uranium-bearing salts: 103; uranium: 152.
Papago Mining District:
Banner mine: uranium oxide: 103.
St. Joe claims: kasolite, uranophane: 103.
Sierrita Mts.: uranium deposit: 103.
Unnamed location in mts.: uranium borosilicate: 91.
Pinal County—
Kate No. 3 claim: pitchblende: 103.
Santa Cruz County—
Annie Laurie claims: pitchblende: 103.
Annie Laurie prospect near Ruby: pitchblende: 101.
Harshaw Mining District: uraninite: 81.
Old Gold No. 1 claim, S. of Annie Laurie claims: uranium oxide: 103.
Oro Blanco Mining District:
Frigita Peak, W. side of: uranium oxide: 103.
Ruby Mining District:
Dry Springs: uranium oxide: 103.
"Spelbrink" claim: uranium in radioactive pyromorphite: 103.
Wrightson Mining District:
Happy Jack mine: pitchblende: 7, 103; uraninite: 81, 82.
Yavapai County—
Black Hills near Jerome: samarskite: 2, 23, 24.
Eureka Mining District on 7-U-7 Ranch near Bagdad: allanite, torbernite: 2; torbernite: 23, 24.
Hillside mine N. of Bagdad: andersonite, bayleyite, pitchblende, swartzite: 103; andersonite, bayleyite, schroeckingerite, swartzite: 3, 138.
andersonite, bayleyite, swartzite: 151; mine development: 17; uranium minerals: 83.
Mesa below Octave and Rich Hill; radium, platinum in black sand, samples analyzed: 119.
Prescott area, three locations: uranium deposits: 168.
W. H. Slaughter's mine near Columbia: pitchblende: 105.
Yarnell Hill area: fergusonite: 23, 24.

Asphaltites, Uranium-bearing
Nevada:
Eureka County—
Unnamed location in Pinon Range, 15 mi. S. of Palisade: 26.

Bibliographies
Arizona: 9, 10, 61, 96.
Nevada: 9, 10, 26.
New Mexico: 4, 9, 10.

Clays, Uranium-bearing
Arizona:
Mohave County—
Aquarius Mts: euxenite: 122.
Nevada:
Lincoln County—
Patterson Mining District:
Cave Valley cave: trace of uranium in clay: 80.

Colorado Plateau
General: 48; carnotite in Entrada and Salt Wash formations: 63.
Carnotite Deposits:
Arizona: 22.
Morrison fm.: 22.
New Mexico: 22.
Shinarump conglomerate: 22.

Copper-Uranium Deposits
Arizona:
Coconino County—
Hack's Canyon in copper mine: 15, 16.
Navajo Bridge, E & N. of: 21.
Mohave County—
Rainbow claims W. of Pipe Springs National Monument: 21.

Fluorite, Uranium-bearin
New Mexico:
General: 95.

Lignites, Uranium-bearing
General:
Nevada: 27.
New Mexico: 62.
Nevada:
General: 27.
New Mexico:
General: 62.

Limestones, Uranium-bearing
General:
New Mexico: 27.
Arizona:
Apache County—
Navajo Indian Reservation: 164.
New Mexico:
General: 27.
McKinley County—
Zuni Uplift: 20.

Navajo Indian Reservation
General:
Arizona, New Mexico, Utah: carnotite: 161.
Arizona, New Mexico, Utah: Navajos may reassign mining rights: 178.

Nevada
General: 12, 13, 25.
Carnotite: 117; in sandstone: 62.
Copper-uranium deposits: 62.
Hydrothermal vein deposits: 62.
Tests by Uranium Vanadium Exploration Co.: 139.
Bibliography: 9, 10, 26.
Churchill County—
Wonder and Fairview, location between: uranium ore "of good grade": 106.
Clark County—
Green Monster mine near Goodsprings: prospecting work to be started: 129; uranium: 129.
Sloan Mining District:
Sloan: carnotite: 26; carnotite in rhyolite joints: 34.
2 mi. S. of: carnotite: 37, 126; carnotite, coating joints in rhyolite: 59.
Sutor Mining District:
Sutor: radium: 26.
2 mi. West of: carnotite: 126.

URANIUM OCCURRENCES (contd.)

Nevada (contd.)
Sutor area: carnotite, patches with manganese oxide in sandstone: 59: several carnotite deposits: 37.
Yellow Pine Mining District:
Goodsprings: carnotite: 126; radium: 26.
2 mi. North of: carnotite: 37; carnotite in sandstone: 59.
Elko County—
Midas: low-grade uranium ore: 156.
Eureka County—
Unnamed location in Pinon Range, 15 mi. S. of Palisade: uranium in asphaltite: 26.
Humboldt County—
Rocky Canyon: pitchblende vein being developed: 188.
Virgin Valley: carnotite in opal: 85.
Lincoln County—
Atlanta Mining District:
carnotite in rhyolite joints and in gold ore: 59; radium: 26.
Atlanta mine: carnotite: 37, 39, 82, 126.
Patterson Mining District:
Cave Valley cave: trace of uranium in clay: 80.
Cave Valley mine: reported uranium and radioactivity not found: 80.
Cave Valley mine of Great Western Co., Caliente: uranium deposit: 123.
Pioche: carnotite in andesite: 34.
50 mi. North of: unidentified carnotite-like mineral: 82.
Lyon County—
Southern part: pitchblende: 155.
Two unnamed locations:
uranium deposits: 130.
Nye County—
Round Mt. near Tonopah:
torbernite and "commercial" uranium: 134.
Heneberg property (or Rainbow claims): uranium deposit: 131, 132; uranium deposits under development: 137, 143.
North Star mine at Tonopah: uranium deposit: 135.
Tonopah: autunite, some 6–8% uranium ore: 157; torbernite and commercial uranium: 133.
Pershing County—
Antelope Mining District:
Majuba Hill: torbernite: 84.

New Mexico
General: 12, 13, 25; torbernite: 118.
Carnotite in sandstone: 46, 62.
Copper-uranium deposits: 62.
Fluorite, uranium-bearing: 95.
Hydrothermal vein deposits: 62.
Lignites, uranium-bearing: 62.
Unnamed location, N.W. part of state: carnotite: 93.
Bibliography: 4, 9, 10.
Colfax County—
President mine near Elizabethtown: uraninite: 104.
Dona Ana County—
Memphis King mine at Organ: secondary uranium mineral: 160.
Grant County—
Big Burro Mt.
Ra-Tor-Plac Co.'s 3 claims, 10 mi. S. of Phelps Dodge camp at Tyrone: autunite, torbernite in diabase dike walls: 56.
Ra-Tor Mining and Manufacturing Co. claims near Tyrone: uranium, radium: 121.
Black Hawk Mining District: pitchblende: 69.
Central Mining District:
Lucky Bill mine at Bayard station: uranium oxide: 114.
Eureka Mining District:
autunite: (?) 69.
White Oaks (should read: White Signal) Mining District, 9 mi. S. of Tyrone: autunite, torbernite: 33.
White Signal Mining District: 92; autunite, torbernite: 54, 69, 102.
A. A. Leach claims near White Signal post office: 113.
Acme claim: autunite, torbernite: 57.
Black Hawk camp at Bullard's Peak, 12 mi. N.W. of Tyrone: pitchblende: 57.
Burro Mts., 4 mi. E. of: autunite, torbernite in diabase dikes: 55.
Camp Kithil near Silver City: kithilite, a copperless torbernite: 111; torbernite: 112.
Foster claim: autunite, torbernite: 57.
Grissom claim: autunite, torbernite: 57.
Merry Widow claim: autunite, torbernite: 57; torbernite: 28.
Merry Widow mine at Silver City: pitchblende, torbernite: 127.
Merry Widow mine shaft: high grade uranium ore: 112.
Otto Forester's radium mine, 1 mi. S. of White Signal post office: torbernite in felsite dike: 19; torbernite ore worth $25 per ton: 19; plan to install concentrating mill: 19.
Shamrock claim, 8 mi. S. of Tyrone: autunite, torbernite: 57.
Signal City: torbernite: 93.
Silver City: torbernite: 99, 115.
Silver City, 2000 acres, 17 mi. from: uranium: 159.
Tullock mine, 8 mi. S. of Tyrone: autunite, torbernite: 57.
Tyrone: kithilite, pitchblende, torbernite: 58.
Hidalgo County—
Sylvanite Mining District: autunite: 60.
McKinley County—
Grants area: development of uranium deposits in Todilto limestone and Brushy Basin member of Morrison fm.: 77; uranium deposits: 88; uranium in Todilto limestone: 29.
Santa Fe Railway land: carnotite, gummite, pitchblende, rutherfordine, tyuyamunite, uranophane in Todilto limestone: 176.
Santa Fe Railway land, Haystack Mt., N. of Prewitt: uranium deposits: 180.
Zuni Uplift: uranium-bearing limestone: 20.
Zuni Uplift area 5 mi. N. of Prewitt: pitchblende and other minerals: 63.

Mora County—
Pidlite pegmatite: microlite: 70.
Rio Arriba County—
General: uranium-bearing lignites: 53.
Petaca Mining District: gummite, samarskite, uraninite, uranophane: 54; samarskite in pegmatite: 70.
Beryl Prospect N. of Cribbensville & S. of Canada la Jarita: gummite, monazite, samarskite, uraninite: 42.
Claim 2½ mi. S.W. of Petaca: gummite, pitchblende, uranophane: 69.
Cribbenville mine, Petaca: monazite with uranium: 66, 69.
Fridlund claim, 2½ mi. S.W. of Petaca: monazite, samarskite, uraninite: 35.
Fridlund dike, 2½ mi. S. of Petaca: fergusonite, samarskite, uraninite, etc.: 69.
Fridlund mine, S. of Canada la Jarita: monazite, samarskite: 42.
Globe mine: monazite, samarskite: 100.
Globe pegmatite: monazite, samarskite: 100.
Las Tablas: samarskite, thorium, etc.: 40.
Lobato mine near Las Tablas: samarskite: 19.
Miller mine, S. of Canada la Jarita: 42.
Petaca: 92.
Sandoval County—
General: uranium-bearing lignites: 53.
Cochiti Mining District: carnotite: 54.
Peralta Canyon: carnotite: 40, 60, 69.
San Juan County—
Farmington: carnotite: 99.
Navajo Indian Reservation:
Carnotite: 140, 161, 172;
Claims subleased to V.C.A. by A.E.C.: 140.
Uranium deposits: 178.
Carrizo Mt.: carnotite: 54.
Carrizo Mts.: carnotite: 86, 87.
East flank: carnotite: 69.
Four Corners area: 172.
Lukachukai Mts.: carnotite: 185; uranium claims: 186.
San Miguel County—
Bull Creek, 15 mi. from Las Vegas: monazite, analysis: 68.
Bull Creek area, 15 mi. W. of Las Vegas: monazite with uranium: 69.
Elk Mt. area, W. of Las Vegas: samarskite: 69.
Las Vegas, S.W. of: cyrtolite, pitchblende: 69.
Santa Fe County—
Glorieta: monazite reported, really from Taos: 67.
Socorro County—
San Lorenzo Gulch, Polvadera Hills, 6 mi. W. of San Acacia: torbernite: 50.
San Lorenzo Mining District: autunite, torbernite, uranophane: (?) 54, 69.
Jerome Copper mine, N.E. side Limitar Mts.: torbernite, uranophane: 40; uranophane: 60.
Scholle: carnotite: 54, 69, 93, 99.
Unnamed location: torbernite: 49.
Taos County—
Harding mine (pegmatite) with beryl, 8 mi. E. of Dixon: microlite: 64, 98, 141.
Harding mine area: unnamed thorium mineral with trace of uranium: 69.
Harding pegmatite: microlite with beryl: 65.
Taos: monazite, reported from Glorieta: 67.
Valencia County—
Copper Hill: uranium oxide with copper: 107.
Grants area: carnotite and schroeckingerite in Morrison fm.: 89;
carnotite in Brushy Basin sandstone: 53;
carnotite in Recapture sandstone: 53;
carnotite in Todilto limestone: 53;
carnotite, tyuyamunite, and uranophane in Todilto limestone: 89;
pitchblende: 89.
uranium deposits: 88.
Operation Haystack, W. of Grants: 170.
Santa Fe Railway land: carnotite: 165, 175; low-grade uranium ore: 172; tyuyamunite in Todilto limestone: 173; uranium deposits: 174; uranium production by Haystack Mountain Development Co., a subsidiary: 177.
Laguna Indian Reservation: 170; 50 mi. W. of Albuquerque: 177.
Anaconda to explore and develop: 181; uranium deposits: 180.

Opal, Uranium-bearing, Occurrences
Nevada:
Humboldt County—
Virgin Valley: carnotite: 85.

Petrified Wood, Uranium-bearing, Occurrences
General: 1.
Arizona:
General: carnotite: 148.
Coconino County—
Lee's Ferry: 21.
Marble Canyon: 21.
Vermillion Cliffs: 16, 144; carnotite: 142, 146.
Navajo County—
Holbrook, S. of: 144.

Pyromorphite, Uranium-bearing, Occurrences
Arizona:
Graham County—
Golondrina claims: 103.
Santa Cruz County—
"Spelbrink" claim: 103.

URANIUM PRICES

Arizona
Apache County—
Navajo Indian Reservation carnotites: percentage to Navajo owners: 140.

Colorado Plateau
Minimum prices guaranteed: 187.

New Mexico
San Juan County—
Navajo Indian Reservation carnotites: percentage to Navajo owners: 140.

United States
Minimum prices guaranteed: 2, 187.

URANIUM PROCESSES

Arizona
Apache County—
Navajo Indian Reservation: mill may be built: 164.
Navajo Indian Reservation carnotites, treatment: Durango, Colorado, plant when rehabilitated by V.C.A.: 140; White Canyon District, Utah, pilot treatment plant: 140.

New Mexico
McKinley County—
Grants area: Anaconda to build plant: 73.
San Juan County—
Navajo Indian Reservation carnotites, treatment: Durango, Colorado, plant when rehabilitated by V.C.A.: 140; White Canyon District, Utah, pilot treatment plant: 140.
Shiprock: uranium ore sampling plant: 47, 185; uranium plant to be built: 161.
Valencia County—
Bluewater area: Anaconda to build mill: 177, 181.
Grants: plant to be built by Anaconda for operation in 1953: 180.

URANIUM PRODUCTION

Arizona
Apache County—
Navajo Indian Reservation: five mines in operation: 147; increase in 1951: 184; mill may be built: 164; 200 t. carnotite ore per day: 147; 200 t. uranium ore mined daily: 144: V.C.A. operations, 200 t. uranium ore daily: 149.
Coconino County—
Flagstaff: uranium oxide concentrates: 116.
Vermillion Cliffs: ore ready for shipment: 144.
Maricopa County—
Morristown: microlite: 17.
Mohave County—
Kingman: samarskite, fergusonite: 17.
Navajo County—
Navajo Indian Reservation: increase in 1951: 184.
Yavapai County—
Prescott area: uranium shipments from three locations: 168.

Colorado Plateau
U.S.A.E.C. Bonus as incentive: 163.

Nevada
Humboldt County—
Rocky Canyon: pitchblende with 0.7% U_3O_8 to be shipped to Colorado Springs ore-buying station: 188.

New Mexico
Grant County—
Big Burro Mt.:
Ra-Tor-Plac Co.'s 3 claims, 10 mi. S. of Phelps Dodge camp at Tyrone: ore mined: 56; ore crushed and dry concentrated: 56; ore marketed as Ra-Tor Plac for medicinal use: 56.
Ra-Tor Mining and Manufacturing Co., Tyrone: ore mill: 121; ore mining: 121.
White Oaks (should read: White Signal) Mining District, 9 mi. S. of Tyrone: 33.
White Signal Mining District: 54.
Camp Kithil: torbernite mining stopped; too hard to process: 112.
McKinley County—
Grants area: Anaconda to build processing plant: 182.
San Juan County—
Shiprock: uranium ore-buying station for Navajo Indian Reservation uranium ores: 182; uranium ore sampling and purchasing depot: 186; uranium ore sampling plant: 47; uranium processing plant to be built: 186.
Valencia County—
Bluewater area: Anaconda to build mill: 177, 181.
Santa Fe Railway land: uranium produced by Haystack Mountain Development Co.: 177.

United States
U.S.A.E.C. Bonus as incentive: Colorado Plateau: 163.

URANIUM PROSPECTING

Arizona
General: 90.
Smithsonian Institution's work: 124.
Colorado Plateau: diamond drilling: 154.
Apache County—
Carrizo Mts.: diamond drilling: 154.

Colorado Plateau
General: diamond drilling: 154.

Nevada
General: 90.
Smithsonian Institution's work: 124.
Clark County—
Green Monster mine near Goodsprings: 129.

New Mexico
General: 90.

United States
Smithsonian Institution, uranium prospecting by: See Arizona, Colorado, Nevada, Wyoming: 124.
Suggestions for prospecting work: 63.

URANIUM PURCHASES

New Mexico
San Juan County—
Shiprock: uranium ore-buying station: 53.

URANOPHANE OCCURRENCES

Arizona
Pima County—
St. Joe claims: 103.

New Mexico
McKinley County—
Grants area:
Santa Fe Railway land: 176.
Rio Arriba County—
Petaca Mining District:
Claim 2½ mi. S.W. of Petaca: 69.
Valencia County—
Grants area, in Todilto limestone: 89.
Socorro County—
San Lorenzo Mining District: (?) 54, 69.
Jerome Copper mine, N.E. side Limitar Mts.: 40, 60.

U. S. Atomic Energy Commission, Div. of Raw Materials, New York, N. Y.

Manuscript Received by the Secretary of the Society, August 20, 1952.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 64, PP. 235-244, 2 FIGS., 2 PLS. FEBRUARY 1953

BEAVERHEAD FORMATION, A LARAMIDE DEPOSIT IN BEAVERHEAD COUNTY, MONTANA

BY WAYNE RUSSELL LOWELL AND MONTIS R. KLEPPER

ABSTRACT

The name Beaverhead formation is proposed for a thick sequence of conglomerate, sandstone, siltstone, and limestone that crops out over an area of at least 400 square miles in Beaverhead County, Montana, extends southward across the Montana-Idaho boundary, and may extend eastward into Madison County. These rocks are clearly sedimentary by-products of the Laramide orogeny and probably range from late Cretaceous to early Eocene.

The Beaverhead formations consists predominantly of conglomerate. In part of the area, an upper and a lower conglomerate member are separated by a middle member of limestone. Where the limestone member is inconspicuous or absent, the upper and lower conglomerate members cannot be differentiated. The most nearly complete and best-exposed known section of the Beaverhead formation, designated the type section, is near the mouth of McKnight Canyon, 6 miles west of Dell, Montana. Here the formation can be divided into four mappable units; elsewhere no more than three units can be recognized. In the McKnight Canyon section, the top and bottom members are dominantly conglomerate, composed of pebbles, cobbles, and subordinate boulders set in a sandy matrix cemented by calcite; breccia beds occur locally. This coarse debris was derived from rocks of Precambrian, Paleozoic, and Mesozoic age and consists largely of limestone and quartzite. The intermediate member consists of two mappable units: a lower thick, massive limestone, locally concretionary, and an upper sequence of interbedded siltstone, sandstone, arkose, limestone, and subordinate conglomerate. At McKnight Canyon, where the base and the top of the formation have been faulted and eroded, the exposed thickness of the section is approximately 9700 feet.

The Beaverhead formation rests unconformably on rocks as young as the Colorado group and as old as early Paleozoic, and it probably rests unconformably upon rocks as young as the Montana group and as old as Precambrian. It is unconformably overlain by vertebrate-bearing fluviatile or lacustrine tuffaceous beds of Eocene and Oligocene age. The coarse debris that composes the formation was eroded from nearby mountains that were uplifted in Late Cretaceous, Paleocene, and early Eocene time, and was deposited in basins adjacent to these mountains. The resulting rocks, a product of Laramide orogeny, were later folded and displaced by overthrusting and block faulting. In places, these rocks are overlain by thrust sheets of Paleozoic rocks.

CONTENTS

TEXT

	Page
Introduction	236
Geologic setting	237
Stratigraphic description	237
General discussion	237
Conglomerate members	237
Limestone member	239
McKnight Canyon section	240
Geologic age	240
Paleontology	240
Structural relations	240
Correlation	241
Geologic history	242
References cited	243

ILLUSTRATIONS

Figure	Page
1. Known distribution of the Beaverhead formation and other conglomerates in Beaverhead and Madison Counties, Montana	236
2. Geologic map of the McKnight Canyon area, Beaverhead County, Montana	237

Plate	Facing page
1. Photographs of the Beaverhead formation	240
2. Photographs of the Beaverhead formation	241

Introduction

The name Beaverhead formation is proposed for the thick sequence of predominantly conglomeratic sedimentary rocks, probably Late Cretaceous to Eocene in age, that crop out over an area of at least 400 square miles in Beaverhead County, Montana, and extend southward across the Montana-Idaho boundary (Fig. 1). Similar rocks along the west flank of the Snowcrest Range in southwestern Madison County, Montana (Fig. 1), may also belong to this sequence, but they are not assigned to it in this paper. An understanding of the Beaverhead formation is believed to be an important key in the eventual deciphering of the Late Cretaceous and early Tertiary geologic history of southwestern Montana.

The Beaverhead formation was not described or mapped in detail by earlier workers. Shenon (1931, p. 17) thought that a thick section of these red and gray conglomerates and sandstones was probably Triassic "Red Beds."

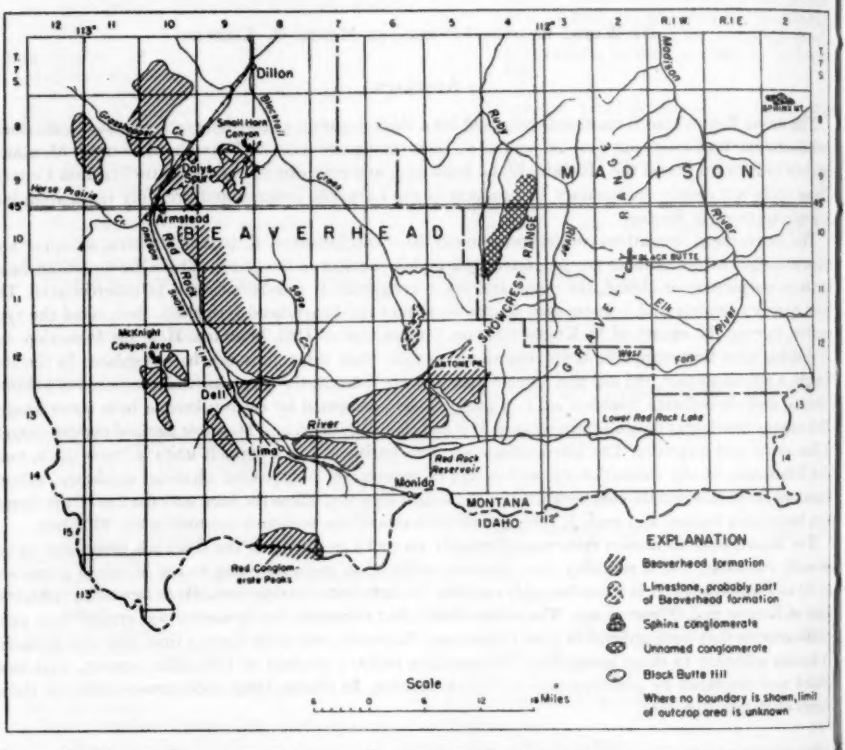


FIGURE 1.—KNOWN DISTRIBUTION OF THE BEAVERHEAD FORMATION AND OTHER CONGLOMERATES IN BEAVERHEAD AND MADISON COUNTIES, MONTANA

Alden (1946) and Pardee (1950, p. 377) refer to part of the conglomerate sequence as early Tertiary and to the red conglomerate and sandstone beds east of Dell as probably Triassic. On the recent reconnaissance geologic map of Montana (Andrews *et al.*, 1944), these rocks are shown as Tertiary "lake beds."

Since the summer of 1946, several geologists of the U. S. Geological Survey, several graduate students of the University of Michigan, and several geologists employed by oil companies have been doing geological work in the region. The authors are deeply grateful for the many

contributions of information pertaining to the Beaverhead formation received from these persons. Suggestions by W. B. Myers and R. W. Swanson of the U. S. Geological Survey were particularly helpful.

Stratigraphic Description

General Discussion

In part of the area of outcrop, the Beaverhead formation can be divided into three members for detailed geologic mapping. The lower and upper members are dominantly conglomerate. The middle member is composed of limestone in most localities where it has been recognized, but at one locality it consists of a unit of limestone overlain by a unit of interbedded siltstone and sandstone with subordinate arkose, limestone, and conglomerate.

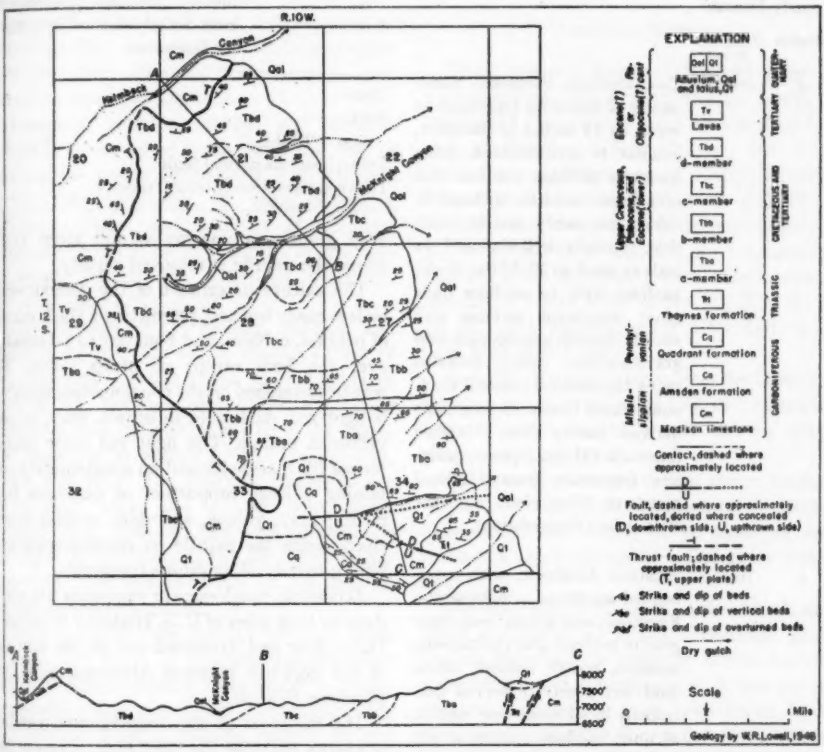


Figure 2.—Geologic Map of the McKnight Canyon Area, Beaverhead County, Montana

Geologic Setting

Precambrian metamorphic rocks, Paleozoic Mesozoic, and Tertiary sedimentary rocks, and Tertiary intrusive and extrusive rocks are exposed in Beaverhead County, Montana.

The Mesozoic and older formations are exposed in truncated, generally north-trending anticlines and synclines that are in part covered by somewhat less-deformed Beaverhead formation. Slightly deformed Tertiary lava flows and tuffs unconformably overlie the older sedimentary rocks. Thrust faults and high-angle normal faults have increased the complexity of the geologic structures (Fig. 2).

Conglomerate Members

The conglomerate members of the Beaverhead formation are poorly exposed in most of the area, but excellent exposures are found in

TABLE 1.—STRATIGRAPHIC SECTION OF THE BEAVERHEAD FORMATION NEAR MCKNIGHT CANYON, BEAVERHEAD COUNTY, MONTANA

Madison limestone (Mississippian)

Thrust fault.

Beaverhead formation (probably Late Cretaceous to early Eocene)

Member	Thickness in feet	
d	3600+	Conglomerate: composed dominantly of limestone fragments as much as 15 inches in diameter, angular to well-rounded, some quartzite pebbles, cobbles, and occasional boulders, enclosed in calcareous, sandy matrix; massive, generally well-stratified, in beds as much as 20–30 feet thick; medium light to medium dark gray; weathered surfaces and mantle develop grayish-pink and grayish-yellow colors; contains many interbedded pale-red sandstone lenses. Limestone fragments derived mostly from Madison limestone (Mississippian); quartzite fragments from Flathead quartzite (Cambrian) and the Belt series (Precambrian).
c	1600±	Siltstone dominant, with interbedded sandstone, conglomerate, limestone, and arkose: very light gray to medium gray; calcareous; massive, poorly bedded; abundant but poorly preserved gastropods in siltstone near middle of unit; residual mantle of red and white quartzite gravel covers most of unit; basal 100 feet consists of calcareous sandstone, arkose, and conglomerate.
b	1000±	Limestone: pinkish gray, yellow-gray, and pale yellowish brown; massively but distinctly bedded; very fine-grained, oölitic and concretionary with concretions as much as 60 mm in diameter; sand grains and angular and rounded larger fragments are present locally; contains some poorly preserved gastropods; several conglomerate beds as much as 20 feet thick are present. Basalt sill, 10–30 feet thick, occurs slightly above the middle of the member.
a	3500+	Conglomerate and breccia: similar to top member, d, but contains fewer quartzite pebbles and cobbles; limestone fragments almost entirely derived from Madison limestone.
Total thickness	9700±	

Talus; conceals normal fault

Thaynes formation (Lower Triassic)

TABLE 1 (cont'd.)

deep gullies, canyon walls, and steep slopes where the mantle is removed rapidly.

The calcareous cement of the conglomerate beds is easily leached, permitting a thick mantle of pebbles, cobbles, and boulders to accumulate over the beds except on steep slopes. The mantle developed on the conglomerate members is light red, dark reddish brown, gray, or pale yellowish orange. The light red color characterizes the mantle formed on conglomerate containing a large proportion of quartzite fragments; gray, yellow, and dark reddish brown characterize the mantle on conglomerate consisting mostly of limestone fragments.

Accessible conglomerate exposures are abundant on both sides of U. S. Highway 91 between Dalys Spur and Armstead and on the east side of the highway between Armstead and Dell, Montana (Fig. 1).

The thickness of the conglomerate members is known only for the McKnight Canyon section where the lower member is approximately 3500 feet thick and the upper member is approximately 3600 feet (Table 1).

The conglomerate members are typically well stratified, consisting of beds as much as 30 feet thick (Pl. 1, fig. 1). Interbedded sandstone lenses are as much as several hundred feet long as exposed in outcrops. Stratification in the conglomerates is emphasized by the interbedded sandstone lenses, size of components in adjacent beds, and color differences. Cross-bedding in the conglomerates has been observed only in Clark Canyon. Channels have been eroded in some conglomerate beds and have been filled by detritus similar to material of the overlying bed.

The conglomerate members consist mostly of

rounded and subrounded pebbles, cobbles, and boulders. Size and shape studies have not been made.

Adjacent conglomerate beds differ from one another markedly in size of components, which are generally quite uniform in size for a particular bed. Boulders 6 to 8 feet in diameter (three boulders more than 20 feet in long diameter have been observed) occur in some well-stratified conglomerate beds.

Limestone pebbles, cobbles, and boulders generally make up as much as 75 per cent or more of the coarse components, and quartzite detritus the remainder. At some exposures, pebbles, cobbles, and boulders of quartzite make up as much as 95 per cent of the conglomerate. Locally the limestone fragments are subangular and angular.

The lithology of the pebbles, cobbles, and boulders indicate the source rocks, as most of the formations of this region have distinctive composition, textures, and colors. Limestone fragments were derived mainly from the Madison limestone as shown by the composition, fossils, and color. The quartzite fragments are white, gray, pink, and red and many show cross-bedding; most of them were presumably derived from the Precambrian Belt series which crops out west and northwest of the area of the Beaverhead formation.

The lithologic composition of the basal zones of both the lower and upper conglomerate members differs notably from place to place; commonly a high percentage of the fragments was derived from a near-by source. In the Dalys Spur-Small Horn Canyon-Armstead area, conglomerate beds contain abundant gneiss and granite cobbles and boulders derived from pre-Beltian rocks. Boulders of marble are abundant locally. These Precambrian metamorphic and igneous rocks are exposed on the west and northeast boundaries of the above area.

The matrix of the conglomerates consists of white, gray, pink, and red sand grains and calcite cement. The pink and red sand grains cause much of the red coloration of the formation. Some sand grains are coated with hematite, but many consist of pink and red quartz.

The distinction between the lower and upper conglomerate members depends upon the presence of the middle limestone member. More detailed studies may confirm the impression that, in general, fragments of Precambrian rocks are more abundant in the upper than in the lower member. Any such criterion, however, must be used with extreme caution, particularly when applied to conglomerates derived very near the source.

Limestone Member

The limestone member observed over an extensive area, was first studied by Lowell at McKnight Canyon and later identified by him east of Grayling, Clark Canyon, and Small Horn Canyon. Limestone of similar lithologic characteristics occurs in Tps. 11 and 12 S., R. 6 W., and in the area of Antone Peak (sec. 23, T. 12 S., R. 5 W.), but its stratigraphic position is not definitely known. The limestone member is 3 feet thick in sec. 12, T. 9 S., R. 10 W., and approximately 1000 feet thick near McKnight Canyon.

In the McKnight Canyon area, the limestone member can be subdivided into two mappable units: a lower limestone unit and an upper siltstone unit (Table 1).

The contacts between the limestone member and the lower and upper conglomerate members have been quite sharp where observed and indicate a rapid change in sedimentary conditions.

The limestone is massive, thick-bedded, and finely crystalline; it is gray, yellowish gray, pinkish gray, or pale yellowish brown. Locally it is porous and concretionary. A few poorly preserved gastropods have been found in it. Some interbedded conglomerate layers are present in the McKnight Canyon section.

The concretionary structures, as much as 60 mm. long, are best seen on weathered surfaces (Pl. 1, fig. 2). Nuclei are generally present, and sand grains are present throughout some concretions. Nuclei consist of sand grains and small rock fragments. The concretions may be closely packed or separated from each other. The concretionary structures in the limestone are similar to the algal pebble limestone of the Green River formation (Bradley, 1929, Pls. 46B–47). Concretionary structures in the hand specimen strongly resemble algal structures, and three thin sections show structures that appear to be of organic origin.

The interbedded conglomerate layers, as much as 20 feet thick, are similar in nearly all respects to the lower and upper conglomerate

units except that boulders are generally not present.

McKnight Canyon Section

The thickest and best-exposed section of the Beaverhead formation observed by the authors here designated the type section, crops out near the mouth of McKnight Canyon in T. 12 S., R. 10 W. (Fig. 2).

The calculated thickness of the section is 9700 feet, and neither the base nor the top of the formation is present. The base of the section is marked by high-angle normal faults which have dropped the Beaverhead formation against the Triassic Thaynes formation and the Mississippian Madison limestone (Fig. 2). The contact between the Beaverhead formation and the Pennsylvanian Quadrant formation is obscured by talus. At the top of the section, a plate of Madison limestone has been thrust over the Beaverhead formation.

The Beaverhead formation as exposed near McKnight Canyon is composed of the three members already described, and in addition the middle limestone member has been subdivided into a lower and an upper unit for detailed mapping purposes shown on Figure 2 as Tbb and Tbc respectively. The stratigraphic section is described in Table 1.

Geologic Age

Paleontology

An early Paleocene age for the middle part of the Beaverhead formation is tentatively indicated by fossil fresh-water gastropods collected from approximately the middle of the siltstone, member C, of the McKnight Canyon section and identified by Teng-Chien Yen (written communication) as follows:

Lioplacodes cf. *L. tenuicarinata* (Meek and Hayden)
Lioplacodes cf. *L. limnaeiformis* (Meek and Hayden)
Amnicola sp. undet.
Hydrobia sp. undet.
Pleurocera cf. *P. warrenanum* (Meek and Hayden)
Goniobasis? sp. undet.
Pleurolimnaea sp. undet.
Physa sp. undet.
Holospira cf. *H. grangeri* Cockerell
Oreohelix sp. undet.

Yen states that, because of the poor preservation of the specimens, the specific identity of several species in the collection cannot be established; therefore the early Paleocene age assignment for the enclosing bed is not too certain, and it may possibly be Late Cretaceous. In the McKnight Canyon section, approximately 4500 feet of the formation had been deposited earlier than the fossil-bearing siltstone. More detailed work in the future may date the formation more precisely.

Structural Relations

Structural relations to older and younger formations indicate that the Beaverhead formation may be very late Cretaceous, Paleocene, or early Eocene. Unconformable contacts with all the underlying formations from Mississippian Madison limestone up to the Cretaceous Colorado group, and possibly the Montana group, have been observed; conglomeratic rocks that may belong to the Beaverhead formation, although they are not here assigned to it, rest unconformably on Precambrian and early Paleozoic rocks along the west flank of the Snowcrest Range. Southeastward from the

Plate 1.—Photographs of the Beaverhead Formation

Figure 1. Stratification in the Beaverhead Formation

Strata are dominantly conglomerates and some thin-bedded sandstone lenses. In Grasshopper Creek Canyon, about 1.5 miles southeast of Bannack, Mont.

Figure 2. Algal (?) Limestone

Concretions are embedded in a sand and grit matrix. Approximately ⅔ natural size.

Figure 3. Angular Unconformity between the Beaverhead Formation (top) and the Triassic Dinwoody Formation and the Permian Phosphoria Formation

High bluff west of Dalys Spur, Montana.

Figure 4. Angular Unconformity between the Beaverhead Formation (top) and the Upper Beds of the Cretaceous Kootenai Formation (bottom)

Half a mile up Grasshopper Creek from its junction with Beaverhead River.

FIGURE 2

FIGURE 4

FIGURE 1

FIGURE 3

PHOTOGRAPHS OF THE BEAVERHEAD FORMATION

FIGURE 2

FIGURE 4

FIGURE 1

FIGURE 3

PHOTOGRAPHS OF THE BEAVERHEAD FORMATION

south side of Grasshopper Creek to the top of the cliff at Dalys Spur (secs. 26 and 35, T. 8 S., R. 10 W.), the Beaverhead formation unconformably overlies the Cretaceous Kootenai formation, Triassic Dinwoody formation, and Permian Phosphoria formation (Pl. 1, fig. 3). An angular discordance of about 25° between the Beaverhead and Kootenai formations is exposed in a dry gulch in the SW¼ SE¼ sec. 11, T. 8 S., R. 10 W. (Pl. 1, fig. 4). An angular unconformity between the Beaverhead formation and the Mississippian Madison limestone (Pl. 2, fig. 1) occurs 2 miles north of Armstead, Montana, on U. S. Highway 91 (NE¼ SE¼ sec. 32, T. 9 S., R. 10 W.). Near the base of Antone Peak (sec. 23, T. 12 S., R. 5 W.) and in the Red Conglomerate Peaks in the headwaters of Sawmill Creek (approximately sec. 33, T. 15 S., R. 8 W.), the Beaverhead formation overlies, probably unconformably, sedimentary rocks tentatively identified as equivalents of the Late Cretaceous Montana group.

Correlation

Yen indicates that the gastropod-bearing bed of the Beaverhead formation may be correlated with the Puerco and the Torrejon formations of New Mexico and with part of the Fort Union formation in Montana.

The Sphinx conglomerate (Peale, 1896, p. 3) in the Madison Range is similar to the Beaverhead formation. Both are dominantly conglomeratic and appear to be sedimentary by-products of Laramide orogeny deposited in relatively depressed areas adjacent to rising mountains. It is not known, however, whether the basins in which these deposits were laid down were interconnected or even strictly contemporaneous, for the chronology of Laramide diastrophism may have been dissimilar in different parts of southwestern Montana. Therefore, the authors consider it advisable to assign a new formational name to the rocks in Beaverhead County, whose age limits and structural relations are reasonably well known, rather than assign them to the Sphinx conglomerate, whose age and structural relations are not well known.

Concerning the Sphinx conglomerate, Peale states,

> "This remnant is between 2,000 and 3,000 feet in thickness, made up of reddish sandstones and hard conglomerates of limestone pebbles and boulders cemented with a reddish sand. The entire mass of the peak is composed of these beds, which are horizontal in position and distinctly stratified. . . . So far as observed the strata are nonfossiliferous, the character of the beds precluding the preservation of fossils. They are, therefore, somewhat arbitrarily referred to the Eocene, but they form a group certainly older[1] than the Bozeman lake beds and younger* than the Livingston formation."

This brief description suggests that the Sphinx is lithologically similar to parts of the Beaverhead formation and that it may have been deposited under similar conditions at about the same time. However, there is no evidence to date the upper limit of the Sphinx, nor do its structural features demonstrate that it was involved in Laramide folding and faulting. The Sphinx might, therefore, be younger than the Beaverhead formation which defi-

* In Peale's report, the wording is actually "younger than the Bozeman lake beds and older than the Livingston beds"; obviously "younger" and "older" were transposed.

PLATE 2.—PHOTOGRAPHS OF THE BEAVERHEAD FORMATION

FIGURE 1. ANGULAR UNCONFORMITY BETWEEN THE BEAVERHEAD FORMATION (TOP) AND MISSISSIPPIAN MADISON LIMESTONE (BOTTOM)

On U. S. Highway 91, 2 miles north of Armstead, Montana.

FIGURE 2. THRUST FAULT IN WHICH A PLATE OF MISSISSIPPIAN LIMESTONE (TOP) HAS BEEN MOVED OVER THE BEAVERHEAD FORMATION

On the west side of U. S. Highway 91, approximately 4 miles north of Armstead, Montana.

FIGURE 3. HIGH-ANGLE FAULT IN WHICH A THRUST PLATE OF MISSISSIPPIAN LIMESTONE (LEFT) HAS MOVED DOWN RELATIVE TO THE BEAVERHEAD FORMATION (RIGHT)

In Grasshopper Creek Canyon, about 1.5 miles southeast of Bannack, Montana.

FIGURE 4. BASALT FLOWS OF PROBABLE EOCENE OR OLIGOCENE AGE OVERLYING EROSIONAL SURFACE DEVELOPED ON THE BEAVERHEAD FORMATION (LOWER RIGHT SIDE)

In Pipe Organ area, 7 miles north of Armstead, Montana.

nitely was involved in folding and is older than upper (?) Eocene. Furthermore, the Sphinx conglomerate is very limited in distribution and is known only at a locality about 40 miles from beds definitely assigned to the Beaverhead formation. In the intervening 40 miles, rocks lithologically similar to the Sphinx and the Beaverhead are known at two localities. In T. 9 S., R. 4 W., along the west flank of the Snowcrest Range, coarse-textured conglomerate and breccia composed predominantly of limestone debris are exposed. Cursory examination of these rocks suggests that they lie unconformably upon Precambrian and early Paleozoic formations, but neither their age nor their relation to an inferred zone of thrust faulting along the west front of the range is known. R. W. Swanson reports (personal communication) that conglomeratic rocks of similar appearance and structural relations occur on the crest of the Gravelly Range, about midway between Sphinx Mountain and the easternmost beds here assigned to the Beaverhead formation. These rocks may be those described by Scott (1938, p. 628–636) and Atwood (Atwood and Atwood, 1945, p. 191–199) as Eocene glacial deposits (Black Butte till). The authors feel that it would be premature to assign the conglomerates in the Snowcrest Range and the Gravelly Range to either the Beaverhead formation or the Sphinx conglomerate until more detailed work is done.

The Paleocene Pinyon formation of Yellowstone National Park and northwestern Wyoming is another predominantly conglomeratic sequence of rocks that was deposited at about the same time as the Beaverhead formation and probably in a similar tectonic environment. On Pinyon Peak, a few miles south of Yellowstone Park, the Pinyon rests with angular unconformity on the Upper Cretaceous Laramie formation and is overlain by later Tertiary acid breccia (Weed, 1896, p. 3). At several localities in the Jackson Hole area, about 30 miles farther south, the Pinyon rests with angular discordance on different Upper Cretaceous sedimentary units (Love *et al.*, 1948, p. 12, 25, 35, 37).

Future detailed geologic mapping may result in the discovery of other bodies of similar conglomerates and associated rocks between the known areas and may furnish additional evidence on the extent, continuity, and correlation of Late Cretaceous and early Tertiary intermontane deposits in southwestern Montana and adjacent areas of Idaho and Wyoming.

Geologic History

The Mesozoic and older formations were folded into generally north-trending anticlines and synclines during the Laramide orogeny. Erosion was rapid on the upper parts of rising folds. The detritus was deposited in near-by newly initiated intermontane basins as a thick sequence of dominant conglomerate and subordinate sandstone, siltstone, and limestone. Terrestrial deposits continued to accumulate on relatively less uplifted structures throughout the period of folding and uplift, as the more uplifted structures were truncated by erosion.

The collected data do not indicate the size or sizes of the intermontane basin or basins in which the Beaverhead formation accumulated, or whether adjacent basins, if present, were interconnected. Most of Beaverhead County seems to have been included in the same basin, because the conglomerate fragments appear to coarsen from east to west in the county, suggesting that much of the debris was derived from the ancestral Beaverhead Mountains along and beyond the west margin of the area of Figure 1.

An early and a late stage of rapid uplift, during which coarse detritus was deposited, were separated by a quiet period during which the medial limestone member was deposited in ponded fresh water.

The concretionary facies of the limestone member probably was deposited at shallow depth and near a shore line (Bradley, 1929, p. 219) as it generally contains abundant sand grains and small rock fragments. Such a sedimentary contact between the concretionary limestone and the Quadrant formation is exposed in the SE¼ sec. 17, T. 9 S., R. 9 W. At this exposure, the limestone is nearly horizontal and abuts against an irregular, steeply dipping surface of the Quadrant formation. Concretionary structures are abundant and are enclosed in a sandy, conglomeratic limestone matrix. The exposure is interpreted as a shallow-water, shoreline deposit because of the angular-

ity of the Quadrant-derived detritus and the attitude of the contact.

These intermontane deposits were involved in folding (Pl. 1, fig. 1), thrust faulting (Pl. 2, fig. 2), and high-angle faulting (Pl. 2, fig. 3) during the later part of the Laramide orogeny. Subsequently, they were deeply eroded and covered by several hundred feet of Tertiary flow rocks and tuffs (Pl. 2, fig. 4), which were also folded, faulted, and eroded.

A later sequence of conglomerates, sandstones, siltstones, and tuffaceous sediments was deposited on the lavas and older rocks. This sequence of terrestrial sedimentary rocks, possibly of Miocene age, is easily recognized by the fresh lava fragments in the conglomerates and sandstone. It has been slightly folded, intruded by basalt dikes, and partly covered by basalt flows south of Bannack, Montana. Valleys and gullies of moderate depth have been eroded into the later rocks.

References Cited

Alden, W. C. (1946) *Physiography and glacial geology of western Montana and adjacent areas*, U. S. Geol. Survey, unpub. ms.

Andrews, D. A.: Lambert, G. S.; and Stose, G. W. (1944) *Geologic map of Montana*, U. S. Geol. Survey, Oil and Gas Invest., Prelim. map 25, sheet 1.

Atwood, W. W., and Atwood, W. W., Jr. (1945) *The physiographic history of an Eocene skyline moraine in western Montana*, Jour. Geol., vol. 53, p. 191–199.

Bradley, W. H. (1929) *Algae reefs and oölites of the Green River formation*, U. S. Geol. Survey, Prof. Paper 154G, p. 203–223.

Love, J. D. *et al.* (1948) *Stratigraphic sections of Jurassic and Cretaceous rocks in the Jackson Hole area, northwestern Wyoming*, Wyo. Geol. Survey, Bull. 40, 48 pages.

Pardee, J. T. (1950) *Late Cenozoic block faulting in western Montana*, Geol. Soc. Am., Bull., vol. 61, p. 359–406.

Peale, A. C. (1896) *Description of the Three Forks sheet, Montana*, U. S. Geol. Survey, Geol. Atlas, Folio 24, 11 pages.

Scott, H. W. (1938) *Eocene glaciation in southwestern Montana*, Jour. Geol., vol. 46, p. 628–636.

Shenon, P. J. (1931) *Geology and ore deposits of Bannack and Argenta, Montana*, Mont. Bur. Mines and Geology, Bull. 6, 77 pages.

Weed, W. H. (1896) *Yellowstone National Park; sedimentary rocks*, U. S. Geol. Survey, Geol. Atlas, Folio 30, 19 pages.

Indiana University, Bloomington, Indiana; U. S. Geological Survey, Washington, D. C.

Manuscript Received by the Secretary of the Society, October 4, 1951.

Publication Authorized by the Director, U. S. Geological Survey.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 64, PP. 245-248 FEBRUARY 1953

Short Notes

EVIDENCE FOR VARIABLE VERTICAL MOVEMENT IN CENTRAL UTAH

BY CLYDE T. HARDY

In a recent paper, *Stress distributions and faulting*, W. Hafner (1951) presented an analysis of stress systems consisting of variable vertical and shearing stress along the bottom of a hypothetical crustal block, deformed in sinusoidal fashion. He included diagrams showing probable faults which should form under conditions of variable vertical uplift. The purpose of the present paper is to direct attention to certain structures in central Utah (Fig. 1) which apparently offer a remarkable example of Hafner's analysis.

The similarity of the structure across the Wasatch Plateau, in central Utah, to the probable fault system derived by Hafner is indeed striking. This relation is illustrated by a schematic structure section (Fig. 2) across the plateau which shows not only a series of antithetic faults, on the west-dipping Wasatch monocline, but also a graben near the upper flexure of the monocline as well as an outward thrust near the base. Outward thrusting, however, is not a common feature near the base of the Wasatch monocline although it is clearly displayed at the point indicated by the structure section. Graben also occur in the central and eastern part of the plateau (Spieker, 1931; 1949). Only faulting of post-Flagstaff age is represented in the structure section, since the pre-Flagstaff structure is extremely complex in this area.

A genetic association of the flexing and faulting of the Wasatch monocline is implied by the similarity of the structure to Hafner's analysis, in spite of a slight divergence in trend of the high-angle faults and the monocline (Spieker, 1949, folded map). High-angle antithetic faults, as well as a graben, also occur in conjunction with a monoclinal structure along the western central margin of the Gunnison Plateau, west of the Wasatch Plateau. The Valley Mountains, west of Gunnison, Utah, and the northern part of the Pavant Plateau, with an intervening graben, present an additional example (Gilliland, 1951). In the latter case, the monoclinal structure is represented by a series of antithetic fault blocks in the Valley Mountains which dip opposite to the Wasatch monocline and the monoclinal structure in the western part of the Gunnison Plateau. These several occurrences suggest a genetic relation of faulting and monoclinal flexing, and in the light of Hafner's analysis, applied to the Wasatch Plateau, this seems to be a necessary conclusion.

Thus it seems reasonable to attribute the monoclinal flexing and associated high-angle faulting, as well as some thrusting, in central Utah to variable vertical uplift. To assert merely that these structural features are the result of tension is inadequate.

REFERENCES CITED

Gilliland, William N. (1951) *Geology of the Gunnison quadrangle, Utah*, Univ. Nebr. Studies, n.ser., no. 8.

Hafner, W. (1951) *Stress distributions and faulting*, Geol. Soc. Am., Bull., vol. 62, p. 373–398.

Spieker, Edmund M. (1931) *The Wasatch Plateau coal field, Utah*. U. S. Geol. Survey, Bull. 819.

—— (1949) *The transition between the Colorado Plateaus and the Great Basin in central Utah*, Utah Geol. Soc., Guidebook to the Geology of Utah, no. 4.

UTAH STATE AGRICULTURAL COLLEGE, LOGAN, UTAH

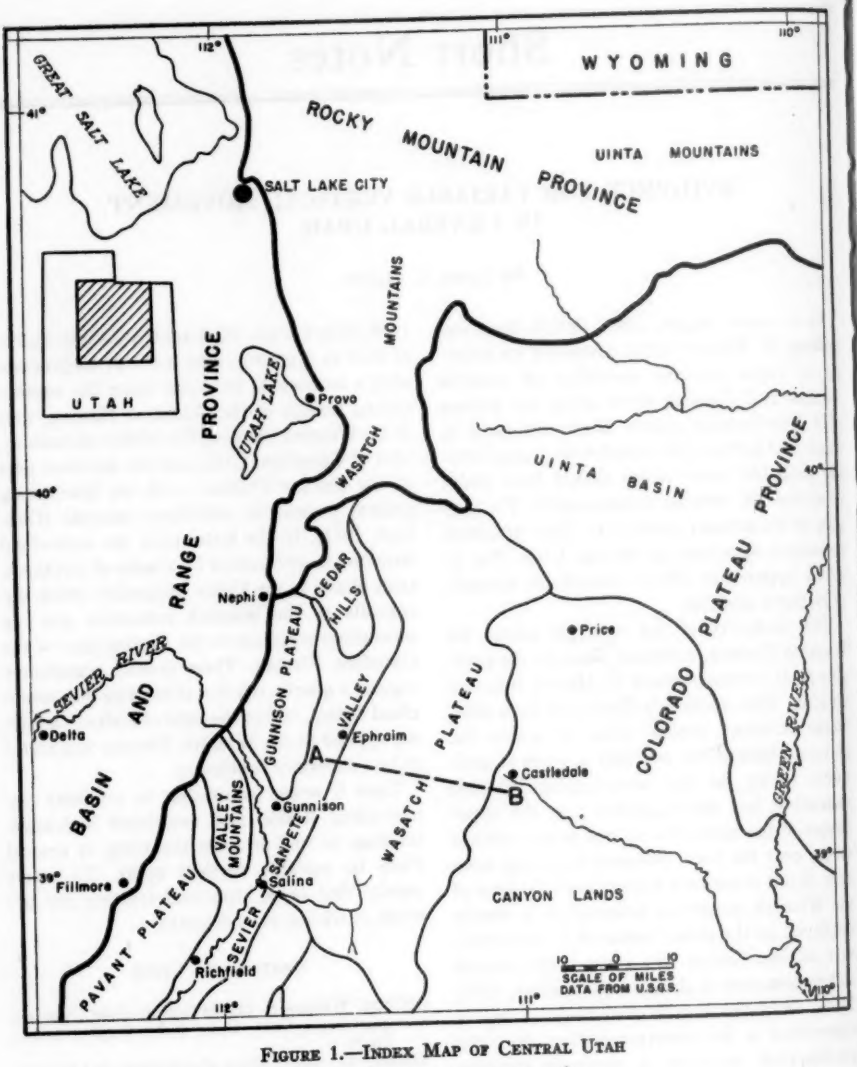


FIGURE 1.—INDEX MAP OF CENTRAL UTAH
Showing location of structure section.

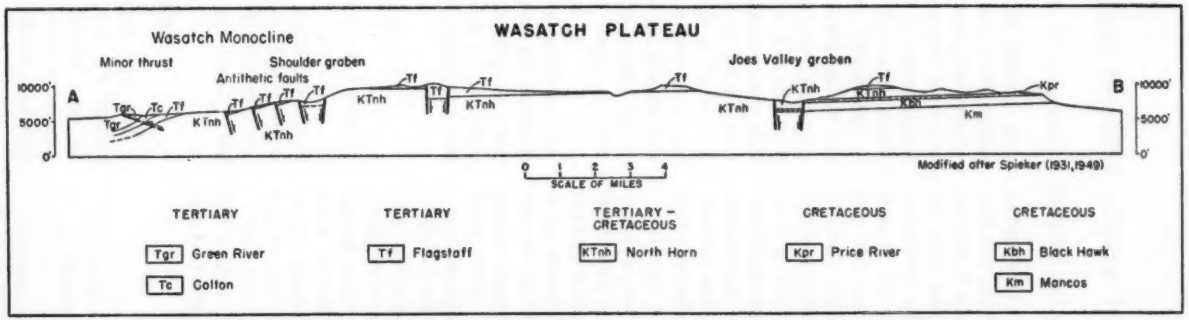


FIGURE 2.—SCHEMATIC STRUCTURE SECTION ACROSS THE WASATCH PLATEAU
Major faults shown.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 64, PP. 249-252 FEBRUARY 1953

SEISMIC-REFRACTION PROFILE ACROSS THE GULF OF MAINE

By Samuel Katz, Richard S. Edwards, and Frank Press

On August 11, 1949, the USS Mentor shot one partially reversed refraction profile across the northern Gulf of Maine, from a point southeast of Portland, eastward beyond Matinicus Rock (Fig. 1, shot 13). Three portable seismographs were set up at Falmouth, near Portland, Maine, on Mt. Desert Island, Maine, and at Crowell, Nova Scotia. The Crowell station was too far to the east to obtain clear ground arrivals from most of the shots. The failure of one of the engines of the Mentor near shot 30 prevented the completion of the run and made it impossible to obtain a fix on the Lurcher Shoal buoy, which would have controlled the shot positions of the eastern half of the profile. As a result the eastern leg remained unreversed, and its results are unreliable.

The data obtained by the Falmouth and Mt. Desert Island recording stations are shown in columns 2 and 3 of Table 1 and Figures 2 and 3. The travel times for shots 3 (36.7 km) through 11 (97.5 km) at Falmouth are well represented by

$$T = 0.95 + X/6.49$$

where X and T are in kilometers and seconds, respectively.

The Mt. Desert Island travel-time curve (Fig. 3) consists of two branches, shots 5 through 14, to the west of the recording stations, falling along the upper branch. The travel time for these shots is

$$T = 0.48 + X/6.09$$

The lack of Loran and visual fixes east of Matinicus Rock (shot 14) and the obscure ground waves recorded at Crowell make an analysis of the lower portion of the travel-time curve at Mt. Desert Island difficult, and none is here presented.

A slight modification of standard methods for interpreting reversed profiles was applied to the case of two listening stations not in line with the course of the shot boat.[1] Using this method, it was found that a surface layer 5.1 km deep, east of Falmouth, with a compressional wave velocity of 5.3 km/sec (unreversed), thins to the east over a distance of about 50 km. The underlying material has a velocity (partially reversed) of 6.25 km/sec, with the interface between the two layers sloping upward to the east at approximately 3°. The travel times computed on the basis of the above assumptions and the difference between the observed and computed travel times are shown in the last column of Table 1.

Although no unique identification of lithologies is possible on the basis of this limited experiment, it seems reasonable to associate the 5.3 km/sec velocity with the granitic rocks of the Maine coast. Various seismic determinations of the compressional wave velocities in granite range from 4.0 to 5.7 km/sec (*e.g.*, Birch, 1940).

An inspection of the results of investigations of the seismic velocities in the earth's crust (*e.g.*, Gutenberg, Leet, Slichter, Tuve, and Tatel) shows that, with few exceptions, a typical range of values for the compressional wave velocity of the upper portion of the earth's crust is 6.0–6.3 km/sec. Our value of 6.25 km/sec lies within this range.

The more detailed results of C. L. Drake and others (1952) corroborate the interpretation here presented.

Acknowledgments

The authors are grateful to P. J. Coyle, J. G. Heacock, Jr., G. L. Shurbet, E. B.

[1] This method is described in Columbia University Technical Report No. 9, issued under Contract W-38-099 ac-396 with the Geophysics Research Division of the Air Force Cambridge Research Center.

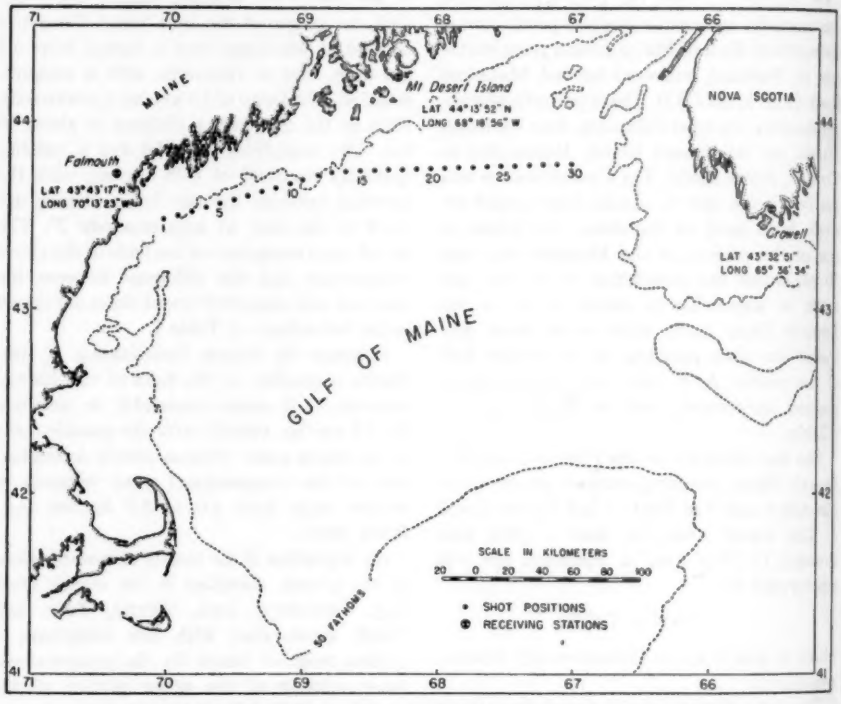


FIGURE 1.—SEISMIC-REFRACTION PROFILE ACROSS THE GULF OF MAINE

TABLE 1.—SEISMIC DATA
Time in seconds

Shot No.	Dist. in Km	Travel Time Observed	Travel Time Computed	Residual Travel Time
3F	36.7	6.67	6.63	+0.04
4F	43.0	7.67	7.65	+0.02
5F	50.4	8.77	8.83	−0.06
6F	58.0	9.94	9.97	−0.03
7F	65.2	11.08	11.00	+0.08
8F	Misfire			
9F	81.2	13.59	13.57	+0.02
10F	89.3	14.78	14.84	−0.06
11F	97.5	16.08	16.07	+0.01
12F	106.2	17.32	17.39	−0.07
5M	126.6	21.19	21.24	−0.05
6M	119.0	20.02	20.03	−0.01
7M	111.6	18.85	18.68	+0.17
8M	Misfire			
9M	96.4	16.14	16.26	−0.12
10M	89.1	15.05	15.04	+0.01
11M	82.1	13.98	13.88	+0.10
12M	74.7	12.65	12.63	+0.02
13M	68.4	11.54	11.59	−0.05
14M	63.2	10.74	10.76	−0.02
13F	114.2	18.55		
14F	122.5	19.62		
15F	131.2	20.83		
1M	158.3	26.10		
2M	150.5	24.79		
3M	142.3	23.79		
4M	134.5	22.23		
25C	156.6	28.27		
26C	148.4	26.91		
27C	140.4	25.50		
28C	132.5	24.20		
29C	Misfire			
30C	116.6	21.58		

F = Falmouth, Maine.
M = Mt. Desert Island, Maine.
C = Crowell, Nova Scotia.

Walden, J. L. Worzel, T. R. Madden, J. Northrop, and G. H. Sutton for their help in seismic recording, and detonating and timing the depth charges. Prof. W. M. Ewing made numerous valuable suggestions. This research was carried out under Contract W-28-Center, Cambridge, Mass., and Contract N6-099 ac-396 with the Geophysics Research Division of the Air Force Cambridge Research

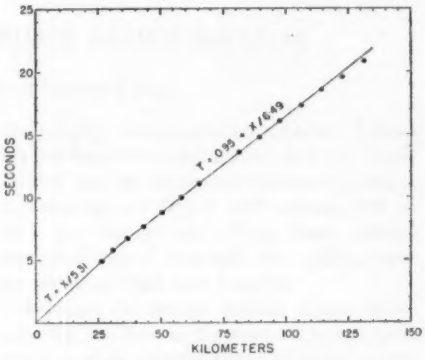


FIGURE 2.—TRAVEL-TIME CURVE, FALMOUTH, MAINE

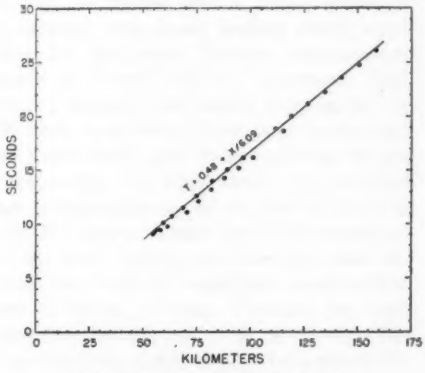


FIGURE 3.—TRAVEL-TIME CURVE, MT. DESERT ISLAND, MAINE

onr-271, Task Order XIII with the Office of Naval Research.

REFERENCES CITED

Birch, Francis (Editor) (1942) *Handbook of physical constants*, Geol. Soc. Am., Spec. Papers, no. 36, 325 p.

Drake, C. L.; Worzel, J. L.; and Beckmann, Walter (1952) *Seismic refraction measurements in the Gulf of Maine* (Abstract), Geol. Soc. Am., Bull., vol. 63, p. 1244

LAMONT GEOLOGICAL OBSERVATORY, COLUMBIA UNIVERSITY, PALISADES, NEW YORK

LAMONT GEOLOGICAL OBSERVATORY CONTRIBUTION No. 74

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 64, PP. 253-254 FEBRUARY 1953

AGE OF A MID-ATLANTIC RIDGE BASALT BOULDER

BY DONALD R. CARR AND J. LAURENCE KULP

The origin and age of the Mid-Atlantic Ridge are still essentially unknown. There are no age measurements available even on the rocks above sea level. In 1947 the ATLANTIS expedition under the direction of M. Ewing obtained several hundred pounds of boulders from depths of 4000 meters from the lower slopes of the Mid-Atlantic Ridge. A large proportion of these boulders consist of eruptive rocks which were described by S. J. Shand (1949) who divided them into three groups: (1) holocrystalline gabbroic rocks; (2) basalts (pillow lavas) with and without olivine; (3) serpentines.

A helium age measurement has been made on one of the fine- grained gray basalt boulders taken at ATLANTIS Station 7, Lat. 3001, Long. 4501, depth 4279 meters. One end of the boulder which measured roughly 8 by 8 by 12 inches has a skin of shiny black glass perpendicular to which is an indistinct radiating columnar structure. All boulders recovered from this station were alike, although various rock types were obtained from some of the other stations. Thin sections of the center portion show about 5 per cent of olivine insets which are perfectly fresh in a groundmass of thin plagioclase laths. The extinction indicates a calcic labradorite. There is no glass. The vesicules amount to about 2 per cent in the thin sections studied. The samples for the age measurement were taken from the center section of the boulder where there was no evidence of alteration.

The helium content of a 10.7349 gram sample was 0.27×10^{-6} cc/gm. Since this is very close to the lower limit of the McLeod gauge used, a blank was made to check possible contamination due to atmospheric helium. This was followed by a sample run using 36.6590 grams. This yielded a result of 0.31×10^{-6} cc/gm. The radium content found was $.031 \pm .002 \times 10^{-12}$ g/g. This was determined by direct fusion release of the radon and measurement of the activity in an ionization chamber. Assuming radioactive equilibrium and a Th/U ratio of 3.5, the calculated values for uranium and thorium are $.085 \times 10^{-6}$ g/g and $.298 \times 10^{-6}$ g/g respectively. Using these values, measured ages of 14.4 and 16.4 million years are obtained from runs 1 and 2.

Although the helium method of age determination has been in disrepute for some years, owing to such complicating factors as helium leakage, surface contamination, and alteration, there remain certain rock types to which it may be applied with a certain degree of confidence. This basalt boulder should represent the ideal case. Previous measurements made by Keevil, Hurley, Goodman, Urry, Strutt, Holmes, and earlier investigators on 86 basic rocks which have been summarized by Keevil (1941) give .45 as an average helium "retentivity." In other words, the measured age is approximately 45 per cent of the true age. The measured ages have been considered as the lower limit of the true age, since the blank run indicated negligible contamination due to helium or neon. Therefore the most probable absolute age is 30 ± 15 my. The upper limit was chosen to allow for a retentivity of only 33 per cent. The error is considered liberal since only 3 of 19 basalts listed by Keevil had a retentivity below this value.

This age is not to be interpreted as the age of the Mid-Atlantic Ridge. A program to determine this would require systematic sampling along and across the ridge. If such a study should yield Tertiary ages for all samples, it would prove a strong argument against certain concepts of origin such as that of continental drift. This program is planned for the future. Since it will require some time to complete the new instrumentation needed for more accurate determination of small quantities of helium, it was considered worth while to make this single result available at the present time.

Studies have been made of the Mid-Atlantic Ridge rocks where they outcrop at the surface at Gough Island, Tristan da Cunha, St. Helena, Ascension, St. Paul, and the Azores (Shand, 1949). It has been assumed that there have been lava flows on the Ridge during the Tertiary. This result on a basalt boulder is significant because it confirms Tertiary volcanic activity on the ocean floor.

The investigation reported in this paper was supported by the Geophysics Branch of the Office of Naval Research, under contract N6onr-27118.

References Cited

Shand, S. J. (1949) *Rocks of the Mid-Atlantic Ridge*, Jour. Geol., vol. 57, p. 89–92.

Keevil, N. B. (1941) *The unreliability of the helium index in geological correlation*, Univ. Toronto Studies, Geol. Ser., no. 46, p. 39–67.

Lamont Geological Observatory (Columbia University), Palisades, New York.

Lamont Geological Observatory Contribution No 76